Project title:Traceability for electrical measurements at millimetre-wave and terahertz frequencies for communications and electronics technologies (TEMMT)

Start date and duration: 1 May 2019, for 3 years and 3 months

Website: http://projects.lne.eu/jrp-temmt/

European Metrology Programme for Innovation and Research (EMPIR) project (part of Horizon 2020)

TEMMT

Traceability for electrical measurements at millimetre-wave and terahertz frequencies for communications and electronics technologies

Introduction

- Millimetre-wave and THz spectrum actively exploited by applications, e.g. 5G (wireless backhaul links), connected autonomous vehicles (radar sensors), space-born radiometers for Earth remote sensing, security imaging…
- Lack of traceability for electrical measurements >100GHz, although measuring instruments commercially available
- This project aims to establish traceability to the SI for 3 electrical measurement quantities: **S-parameters**, **Power**, **Material properties** (complex permittivity), at millimetre-wave and THz frequencies



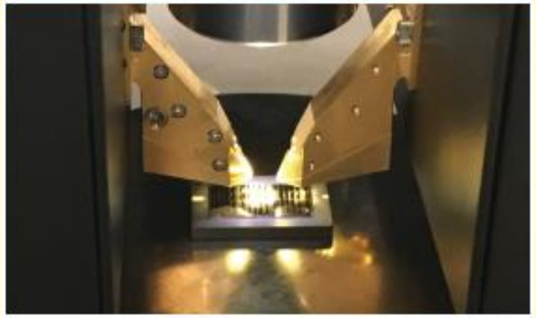

Objectives and workpackages overview

WP1: Traceable connectorised S-parameter measurements

- Develop new metrology for waveguide to 1.5 THz
- Establish traceability for E-connector for 5G and automotive radars
- Exploit outputs from previous EMRP project SIB62 (HFCircuits)

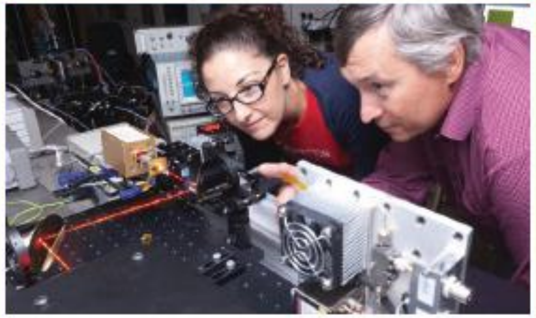
WP2: Traceable planar S-parameter measurements

- Improve on-wafer measurements to 1.1 THz
- Develop new planar calibration/ verification standards
- Exploit outputs from previous EMPIR project 14IND02 (PlanarCal)



WP3: Traceable power measurements

- Extend calorimeters and transfer standards above 100 GHz
- Investigate traceability for commercial power meters at THz frequencies



WP4: Traceable material measurements

- Investigate material properties over a wide frequency range (140-750 GHz)
- Establish traceability for commercial material characterisation kits at THz frequencies

WP5: Creating impact

Knowledge transfer:

- Standards: IEEE P287, IEEE P1785, IEC TC46, IEEE On-wafer Group
- ≥ 6 journal papers, ≥8 conference papers, ≥1 trade journal article
- Public reports on EURAMET comparisons for measurements of power and materials
- Technical Advisory Group

Training:

- 2 workshops delivered at annual European Microwave Week
- 2 training courses delivered at Project Partner locations
- Practical lab demonstrations of new measurement techniques using commercial equipment
- Researcher visits at key Project Partner organisations

Uptake and exploitation:

- Exploitation plan for disseminating developed standards and customer calibration services
- Comprehensive measurement capability based on outputs from this project and earlier European projects (SIB62, 14IND02)
- Establish link with European Microwave Association to increase project uptake
- Proposal to EURAMET for a coordinated network of EU NMIs

19 Participants: 9 NMIs + 5 research institutes + 5 companies

- NPL, CMI, GUM, LNE, METAS, PTB, TUBITAK, VSL, INTI
- Birmingham University, Chalmers University of Technology, Ferdinand-Braun-Institut (FBH), University of Lille, Military University of Technology in Warsaw
- Anritsu, FormFactor, Keysight, Rohde & Schwarz, VDI

TEMMT

Traceability for electrical measurements at millimetre-wave and terahertz frequencies for communications and electronics technologies

WP1: Establishing Traceability to 90 GHz for the 1.35 mm Precision Coaxial Connector

NPL
National Physical Laboratory

Nick Ridler, James Skinner and Dan Stokes

National Physical Laboratory, UK

1st TEMMT Training Course (online), 21st July 2021

Overview

1. General Introduction – Nick Ridler (5 minutes)

2. Dimensional Traceability – Dan Stokes (15 minutes)

3. Electrical Traceability – James Skinner (15 minutes)

1. General Introduction

- Work Package 1 (WP1) – Description
- The 1.35 mm Precision Coaxial Connector
- The Research Team

WP 1 – Description

Purpose: To develop traceability and verification techniques for S-parameters

In 2 parts:

(i) Coaxial line: 1.35 mm connector to 90 GHz

(ii) Waveguide: in 3 bands covering 330 GHz to 1.5 THz

WP 1 – Description

Purpose: To develop traceability and verification techniques for S-parameters

In 2 parts:

(i) Coaxial line: 1.35 mm connector to 90 GHz

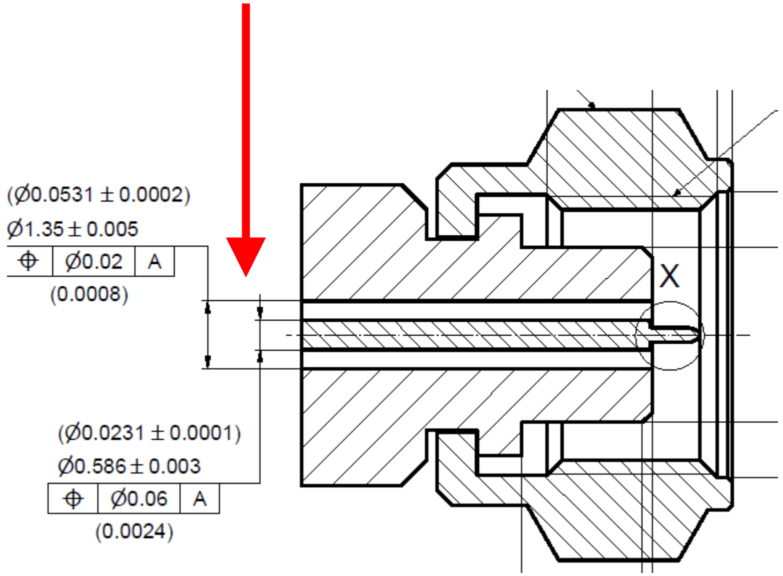
(ii) Waveguide: in 3 bands covering 330 GHz to 1.5 THz

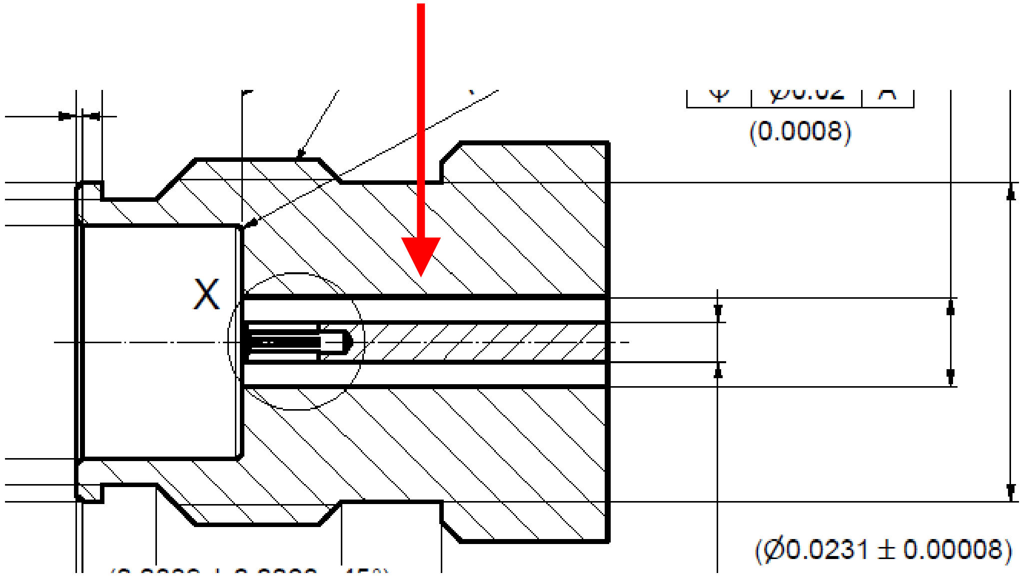
1.35 mm Coaxial Connector

- A precision connector (with air interface)
- A “new” connector – introduced in the past few years
- Designed for communications and radar related applications
- Standardised in IEC 61169 (Part 65)
- Standardisation in IEEE Std 287 is on-going

1.35 mm Coaxial Connector

- Recommended frequency range: DC to 90 GHz
- The E-band connector, or, “E connector”
- Internal diameter of outer conductor = 1.35 mm





The Research Team

Consortium of 4 world-leading National Metrology Institutes (NMIs):

INTI, Argentina

LNE, France

NPL, UK

PTB, Germany

2. Dimensional Traceability

- What is our goal?

- Why Dimensional?

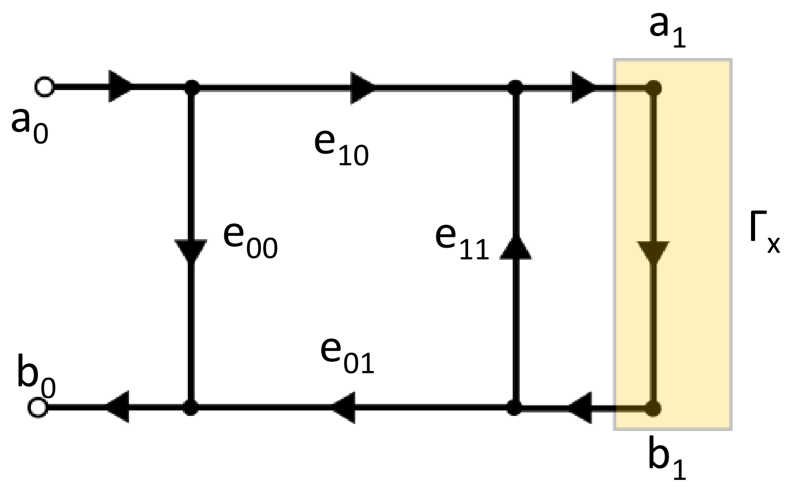
- Line diameters and measurements

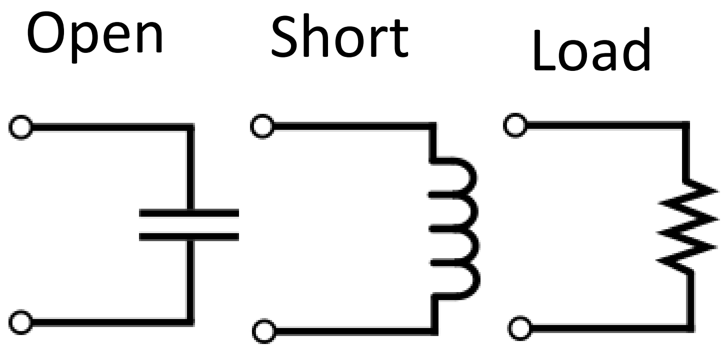
- Challenge of connectors

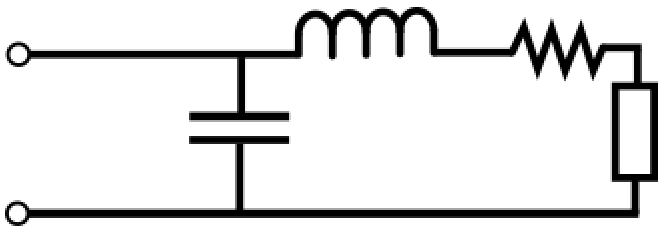
- Comparison

WHAT ARE WE TRYING TO ACHIEVE?

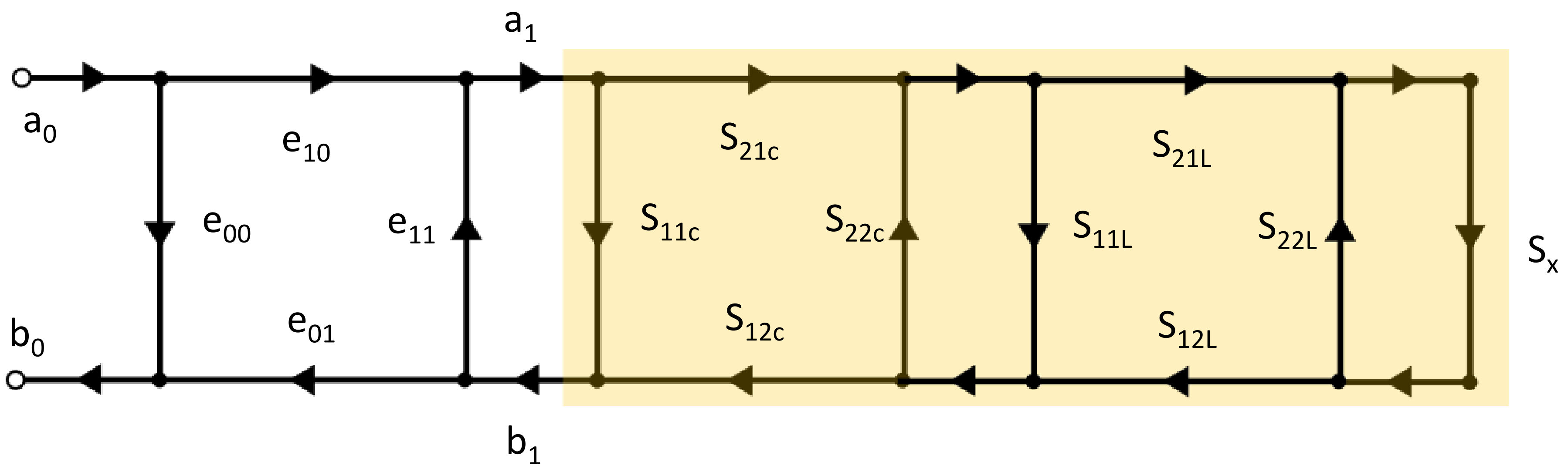
A simple 1 port network.







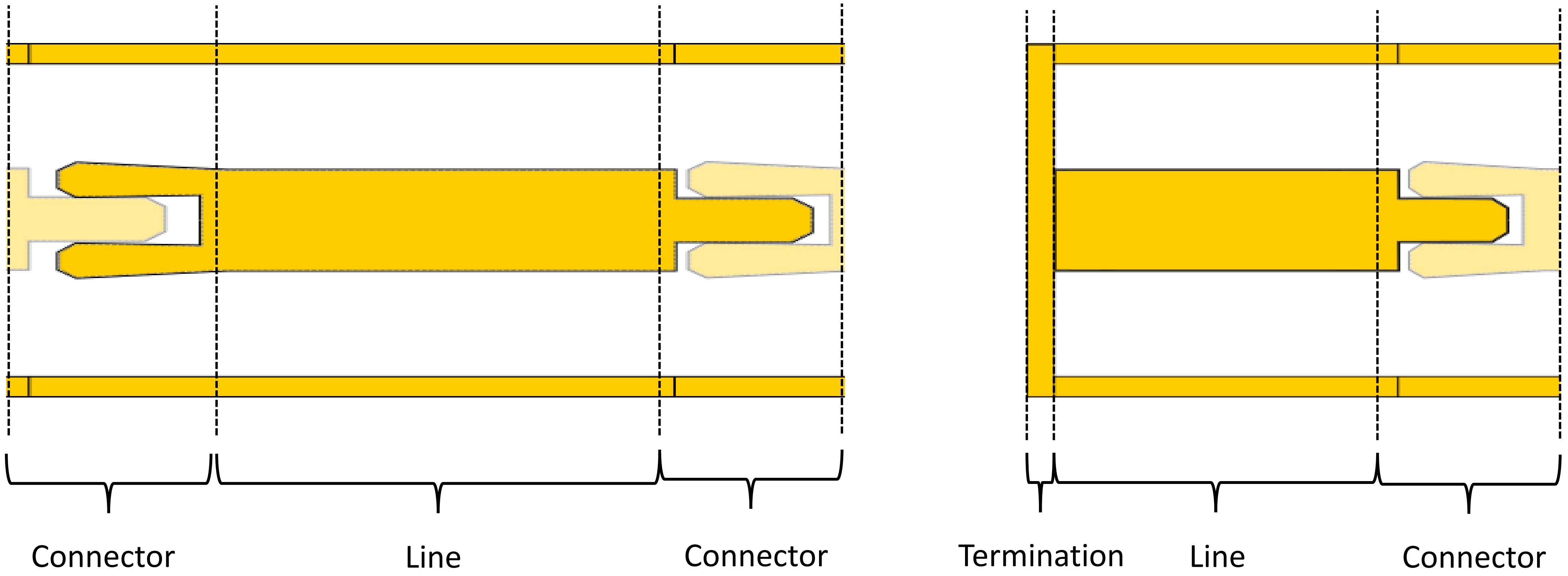
A “less” simple 1 port network.



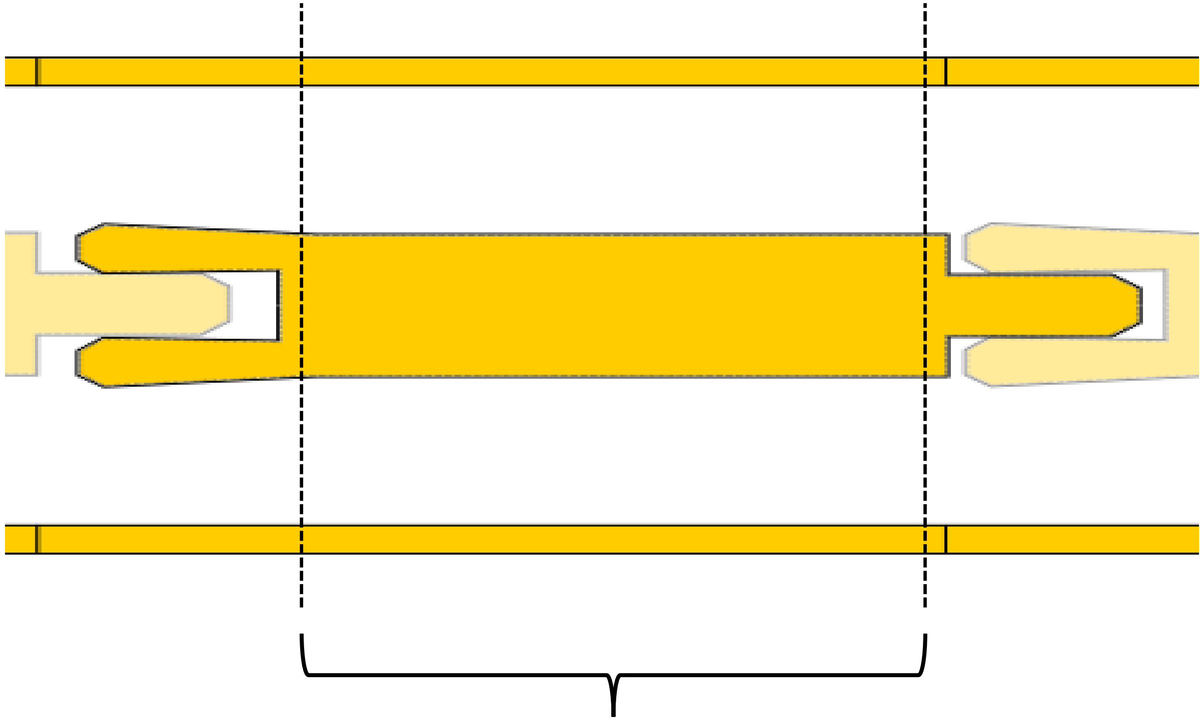
What is S_{xxc} and S_{xxL} ?

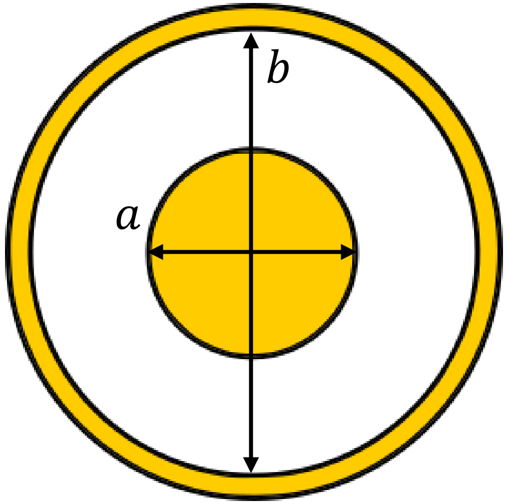
$$\Gamma_x = S_c \oplus S_L \oplus S_x$$

WHY START WITH DIMENSIONAL METROLOGY?



LINES





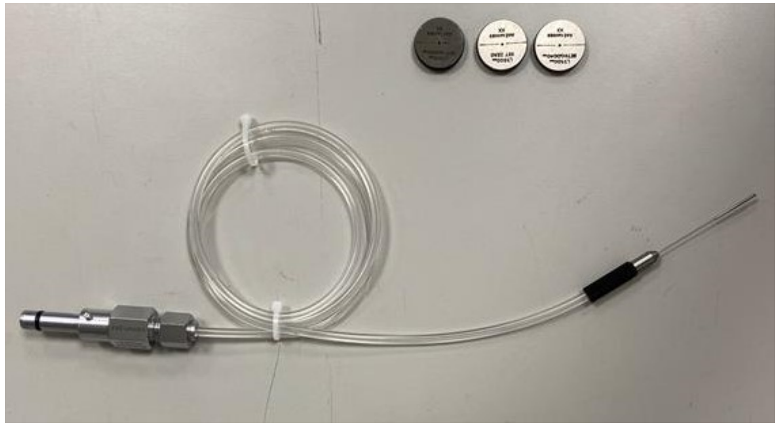
$$Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\, ln\left(\frac{b}{a}\right) \cong 59.94 \times ln\left(\frac{b}{a}\right)$$

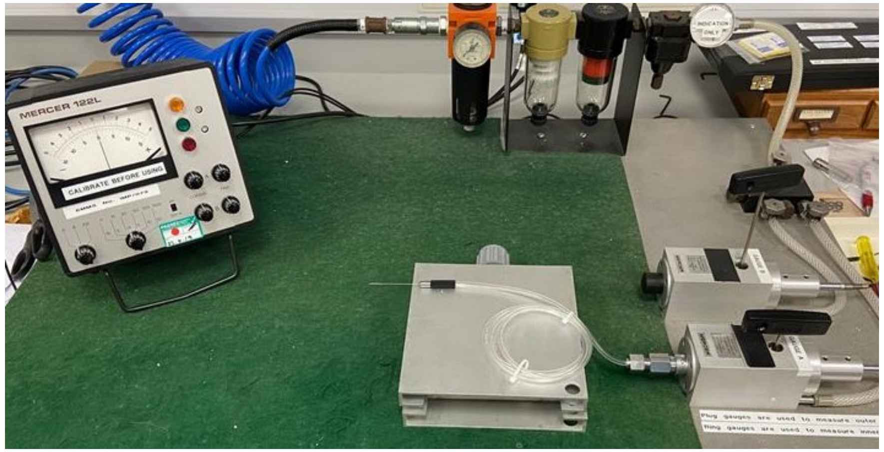
$$Z = \sqrt{\frac{(R + j\omega L)}{(G + j\omega C)}}$$

MEASUREMENT SETUPS

Outer conductor inner diameter

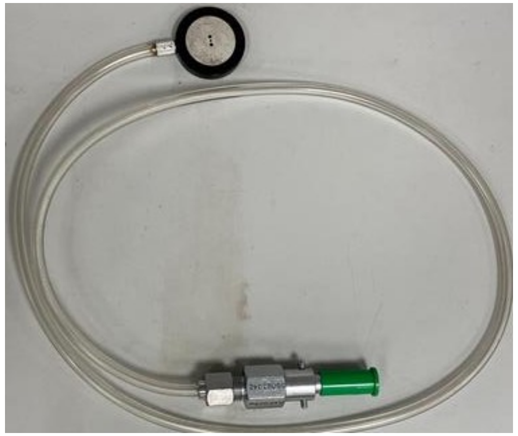
Air Plug Gauge



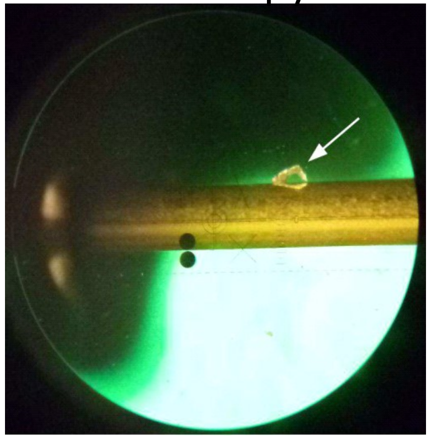


Inner conductor outer diameter

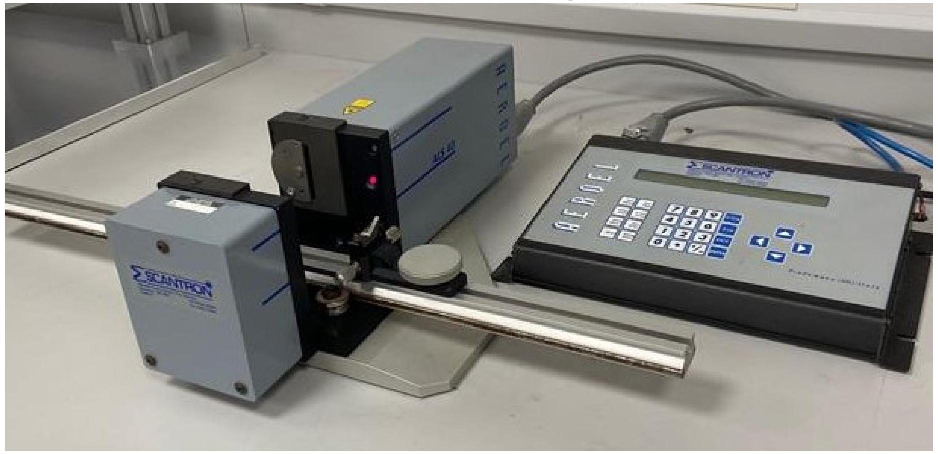
Air Ring Gauge



Microscopy



Laser Gauge



UNCERTAINTY

Outer conductor using air gauging system

Description	Contribution		Sensitivity coeff	Distribution	Divisor	Inverse degrees of freedom	Overall, um
Lab temperature	2	°C	1.49E-02	Rectangular	1.73	0	0.017
Resolution	0.5	um	0.5	Rectangular	1.73	0	0.14
Parallax error	0.5	um	1	Rectangular	1.73	0	0.29
Probe linearity	0.2	%	0.15	Rectangular	1.73	0	0.017
Meter accuracy	1	%	0.15	Rectangular	1.73	0	0.087
Probe repeatability	0.1	um	1	Gaussian (k = 1)	1	0.0010	0.10
Flow adjuster hysteresis	0.519	um	1	Rectangular	1.73	0	0.30
Std dev of measurements	0.79	um	0.26	Gaussian (k = 1)	1	0.071	0.20
Calibration standard history	0	um	1	Gaussian (k = 1)	1	0	0
Calibration standard uncertainty	0.8	um	1	Gaussian (k = 2)	2	0	0.40
					Total	0.00071 1410	0.6427
					Coverage factor		2
					Expanded uncertainty		1.29
					(c.f. k = 2)		1.29

Measured deviations from nominal		Std Dev		
Outer diameter average	0.500um	0.79um	=>	**1.3505mm ± 1.29um @ k = 2**

UNCERTAINTY

Inner conductor using laser gauge

Description	Contribution	Sensitivity coeff	Distribution	Divisor	Inverse degrees of freedom	Overall, um
Resolution	0.1 um	0.5	Rectangular	1.73	0	0.029
Lab temperature	2 °C	0.0064	Rectangular	1.73	0	0.0074
Cal standard misalignment	0.05 mm	0.033	Rectangular	1.73	0	0.00094
Gauge repeatability	0.1 um	1	Gaussian (k = 1)	1	0.0010	0.10
Height error	0.4 um	1	Rectangular	1.73	0	0.23
Laser noise	0.2 um	1	Gaussian (k = 1)	1	0	0.20
Inner conductor position	0.05 mm	0.059	Rectangular	1.73	0	0.0017
Calibration standard history	0 um	1	Gaussian (k = 1)	1	0	0
Calibration standard uncertainty	0.5 um	1	Gaussian (k = 2)	2	0	0.25
Std dev of measurements	0.21 um	0.26	Gaussian (k = 1)	1	0.071	0.055

Total	2.67693E-05 37356	0.4121
Coverage factor		2
Expanded uncertainty		0.82
(c.f. k = 2)		0.82

Measured deviations from nominal		Std Dev	
Inner diameter average	0.180um	0.21um	=> **0.5862mm ± 0.82um @ k = 2**

UNCERTAINTY

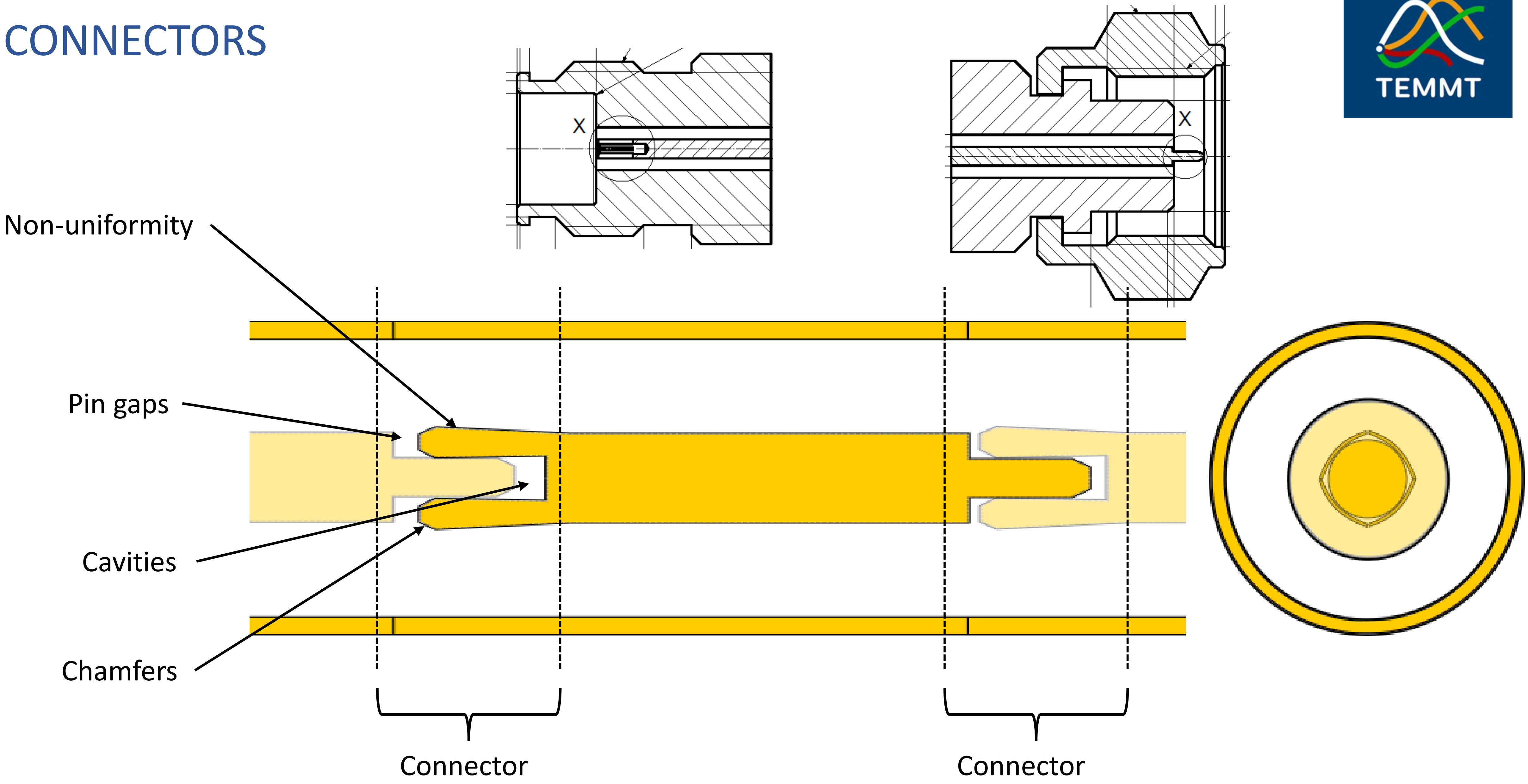
Characteristic Impedance

$$Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\,ln\left(\frac{b}{a}\right) \cong 59.94 \times ln\left(\frac{b}{a}\right)$$

Description	Contribution	Sensitivity coeff	Distribution	Divisor	Inverse degrees of freedom	Overall, Ohm
Outer conductor radius	0.6427um	0.044	Gaussian (k = 1)	1	0.00071	0.029
Inner conductor radius	0.4121um	0.10	Gaussian (k = 1)	1	2.68E-05	0.042
Permittivity	0.000078	25	Rectangular	1.73	0	0.001
				Total	8.26E-05 12112	0.051
				Coverage factor		2
				Expanded uncertainty		0.10

Characteristic impedance **50.025 Ω ± 0.102 Ω @ k = 2**

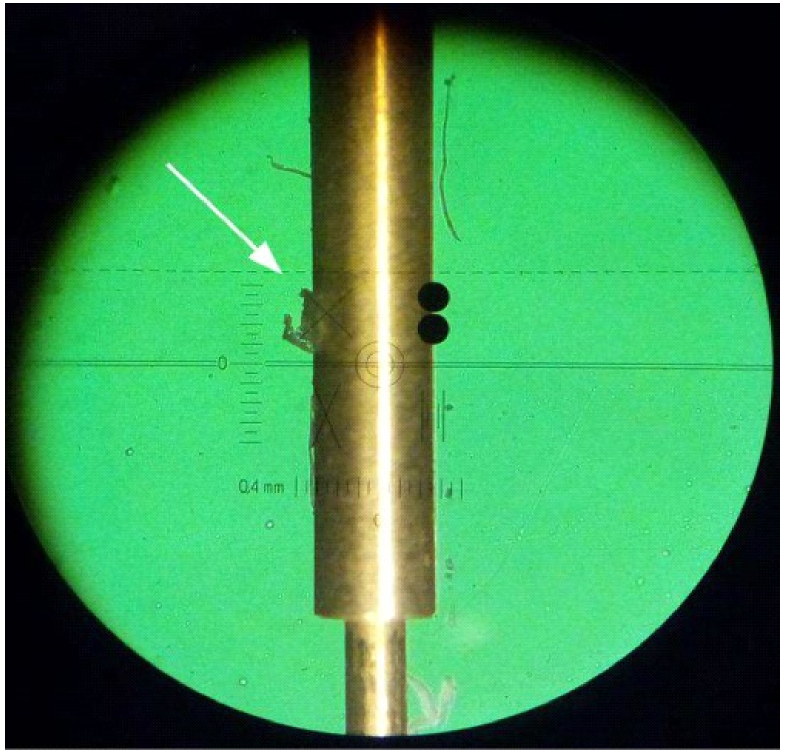
CONNECTORS


X
X
Non-uniformity
Pin gaps
Cavities
Chamfers
Connector
Connector

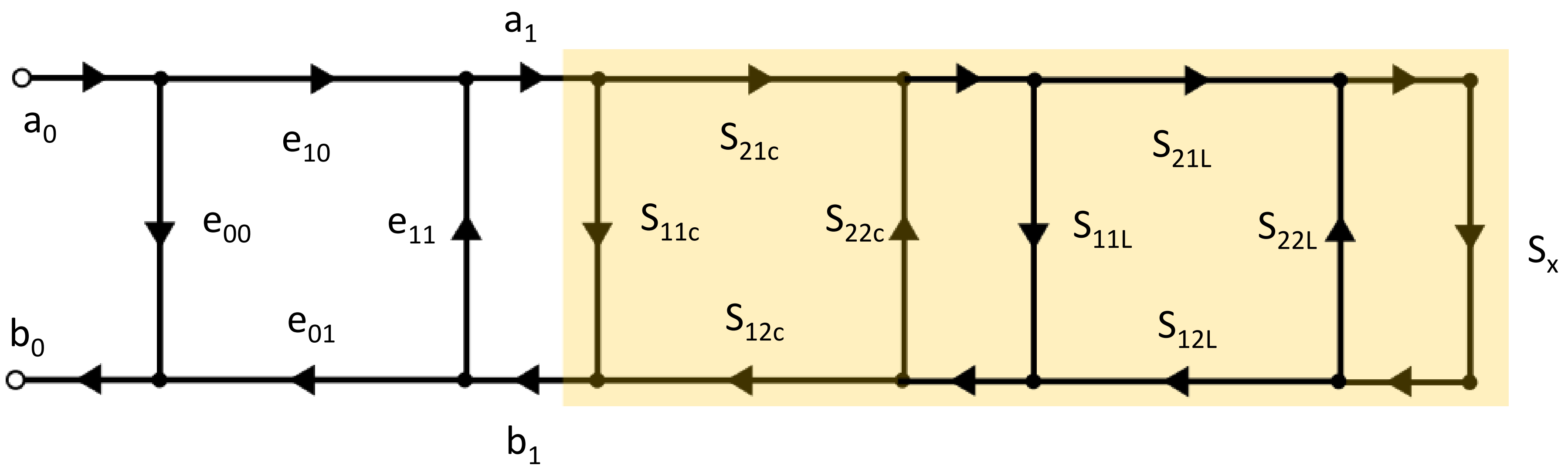
MEASUREMENT SETUPS

Micro co-ordinate measurement machines (µCMM)

Microscopy



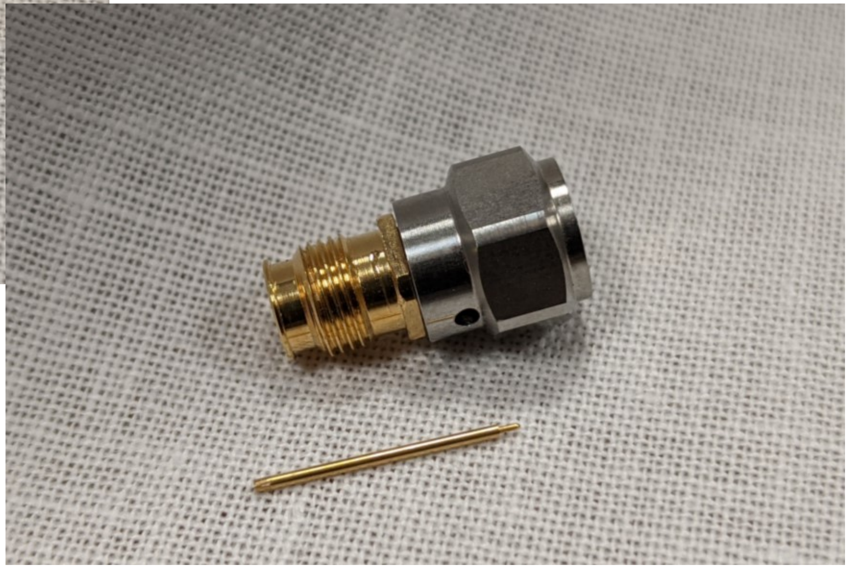
A “less” simple 1 port network.



$$\Gamma_x = S_c \oplus S_L \oplus S_x$$

COMPARISON

- Comparison of conductor diameters and characteristic impedances.
- 2 traveling standards: Beadless airlines.
- 5 participants:



National Physical Laboratory

Electrical Metrology: Key Challenges

Outline

NPL National Physical Laboratory

- Challenges in electrical metrology
  - Sourcing Components
  - Choice of calibration scheme
  - Measurement setup - Interfacing
  - Uncertainty Analysis
- S-parameter Results
- Next Steps for 1.35 mm capability
- Opportunities for 1.35 mm coaxial

Establishing Measurement Capability in 1.35 mm Coaxial

NPL
National Physical Laboratory

?

Challenge: Sourcing Components

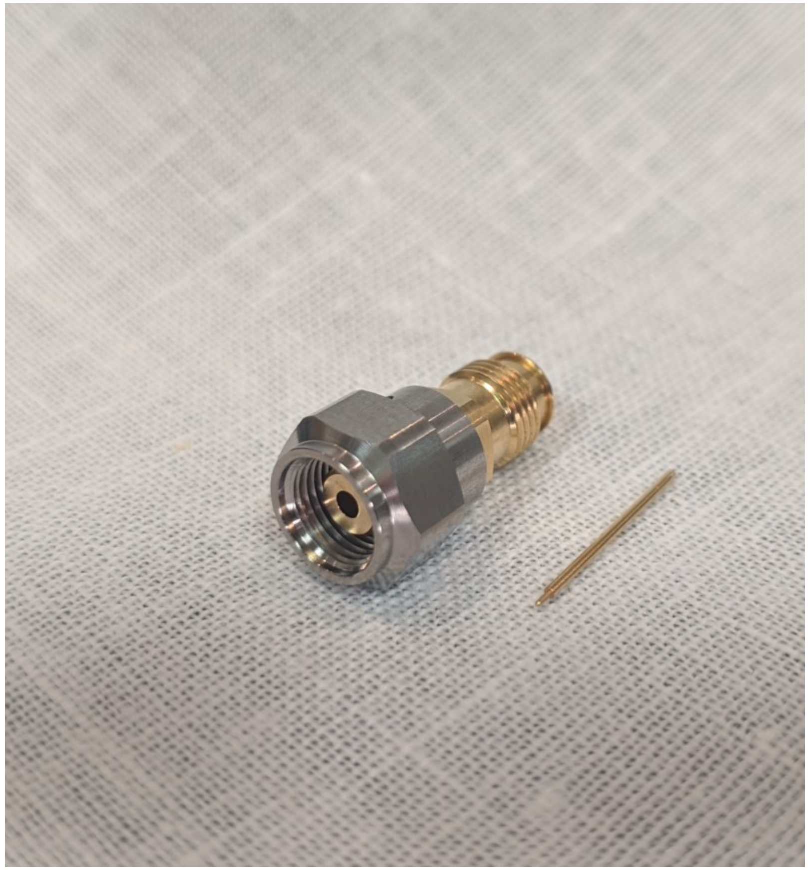
- New 1.35 mm connector recently introduced to market
- Gradual uptake, still only a limited number of suppliers selling 1.35 mm components
- Currently available off the shelf:
  - Various waveguide to 1.35 mm adaptors
  - 1.85 mm to 1.35 mm coaxial adaptors
  - 1.00 mm to 1.35 mm coaxial adaptors
  - 1.35 mm to 1.35 mm coaxial adaptors (through device)
  - Calibration Standards: Short Circuits, Open Circuits, 50 Ohm Loads, Offset Short Circuits
- Some custom devices available
  - Airlines, mismatch adaptors

Challenge: Choice of Calibration Scheme

- Calibration required to take accurate measurement through correction of errors present in the system
- Quality of calibration proportional to knowledge of calibration standards
- Choice narrowed by ability to characterise calibration standards

Challenge: Choice of Calibration Scheme

- TRL – Through Reflect Line
  - Through: Cabled connection between ports 1 & 2
  - Reflect: Short-circuit standards (male & female) connected to ports
  - Line: Section of coaxial line of known length, known as an 'airline'
  - Consistent full-band calibration achieved through choice of airline lengths
  - Multiple airlines typically used. Effectiveness of line assessed at each frequency to ensure suitable standard is available for across whole of desired frequency band
  - Traceability based on calculation of characteristic impedance of airlines – derived from diameters of the inner and outer conductors of the coaxial line



Challenge: Choice of Calibration Scheme

- SOLT – Short Open Load Through
  - Short: 1-port Short-circuit standard (reflect)
  - Open: 1-port open-circuit standard (reflect)
  - Load: 1-port 50 Ohm termination standard (absorb)
  - Through: Cabled connection between ports 1 & 2
  - Traceability based measurement of characteristics of standards, or database of reflection coefficients

Challenge: Choice of Calibration Scheme

- SOOT – Multiple Offset Short Through
  - Short: 1-port Short-circuit standard (reflect)
  - Offset short: 1-port Short-circuit standard (reflect) with offset of known length
  - Through: Cabled connection between ports 1 & 2
  - Might have upwards of 5 offset short-circuits
  - Can also utilise open, load standards
  - Consistent full-band calibration achieved through choice of short-circuit offset lengths
  - Traceability based on dimensional characterisation of offset short-circuits

Challenge: Choice of Calibration Scheme

- Main factors in decision:
  - Availability of components
  - Ability to characterise standards – dimensional capability
  - Compatibility with measurement setup

Challenge: Measurement Setup

- Equipment required to achieve setup capable of measuring in 1.35 mm coaxial to the full extent of its capability i.e. up to 90 GHz

- Main limiting factor is access to VNA
  - E-Band not accessible to VNAs with 2.4 mm connector or larger / only 2 ports

- Single setup for full band / multiple banded setups

Challenge: Measurement Setup

Case 1: 1.0 mm VNA

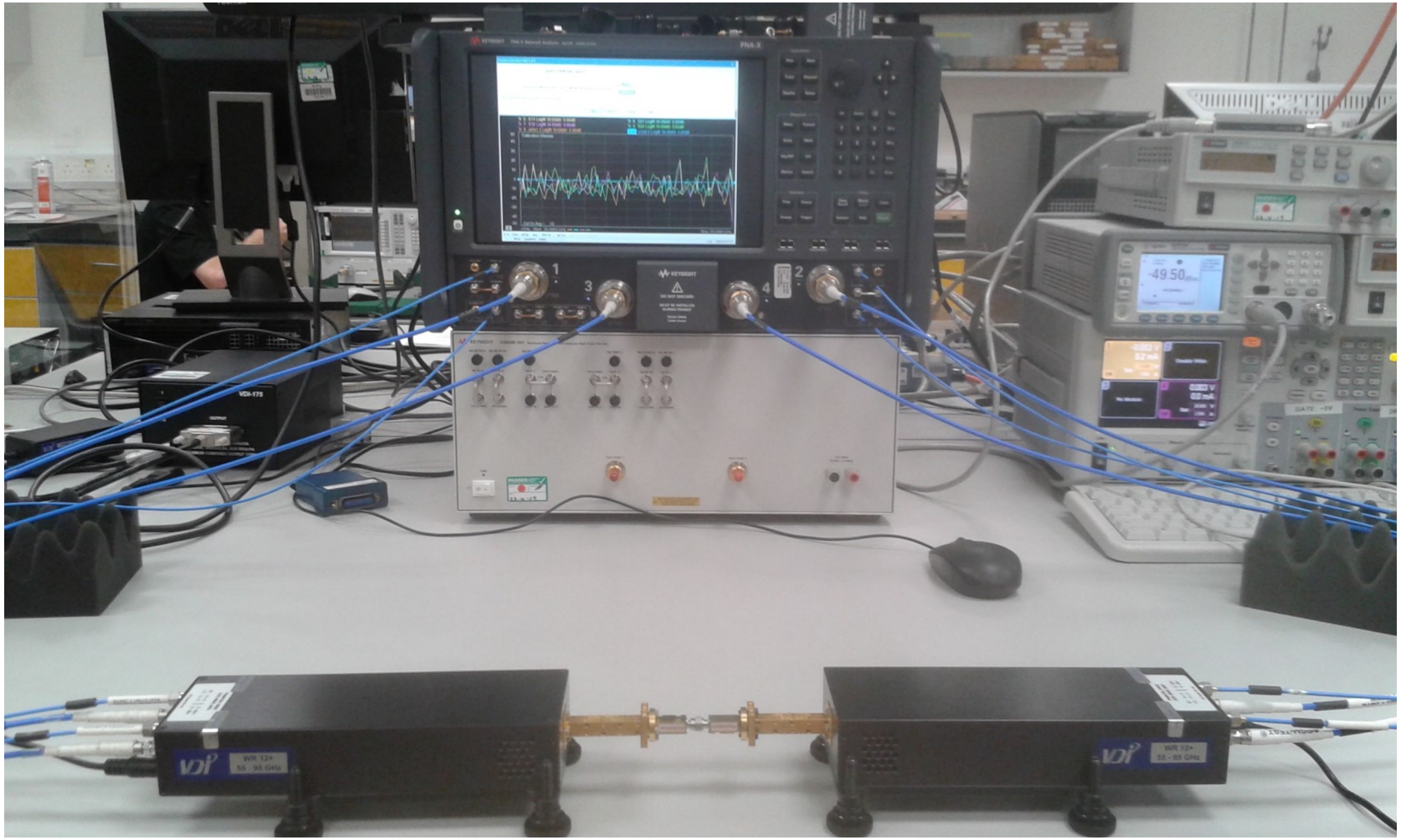
- VNA: Keysight N5290A PNA Millimeter Wave System
- Port connectors: 1.0 mm – 110 GHz upper limit
- Connections: 1.0 mm cables connected to ports 1 & 2
- Adaptors: Rosenberger 1.0 mm (f) to 1.35 mm coaxial adaptors (m & f)
- Frequency range: Full-Band up to 90 GHz

Challenge: Measurement Setup

Case 2: 1.85 mm VNA

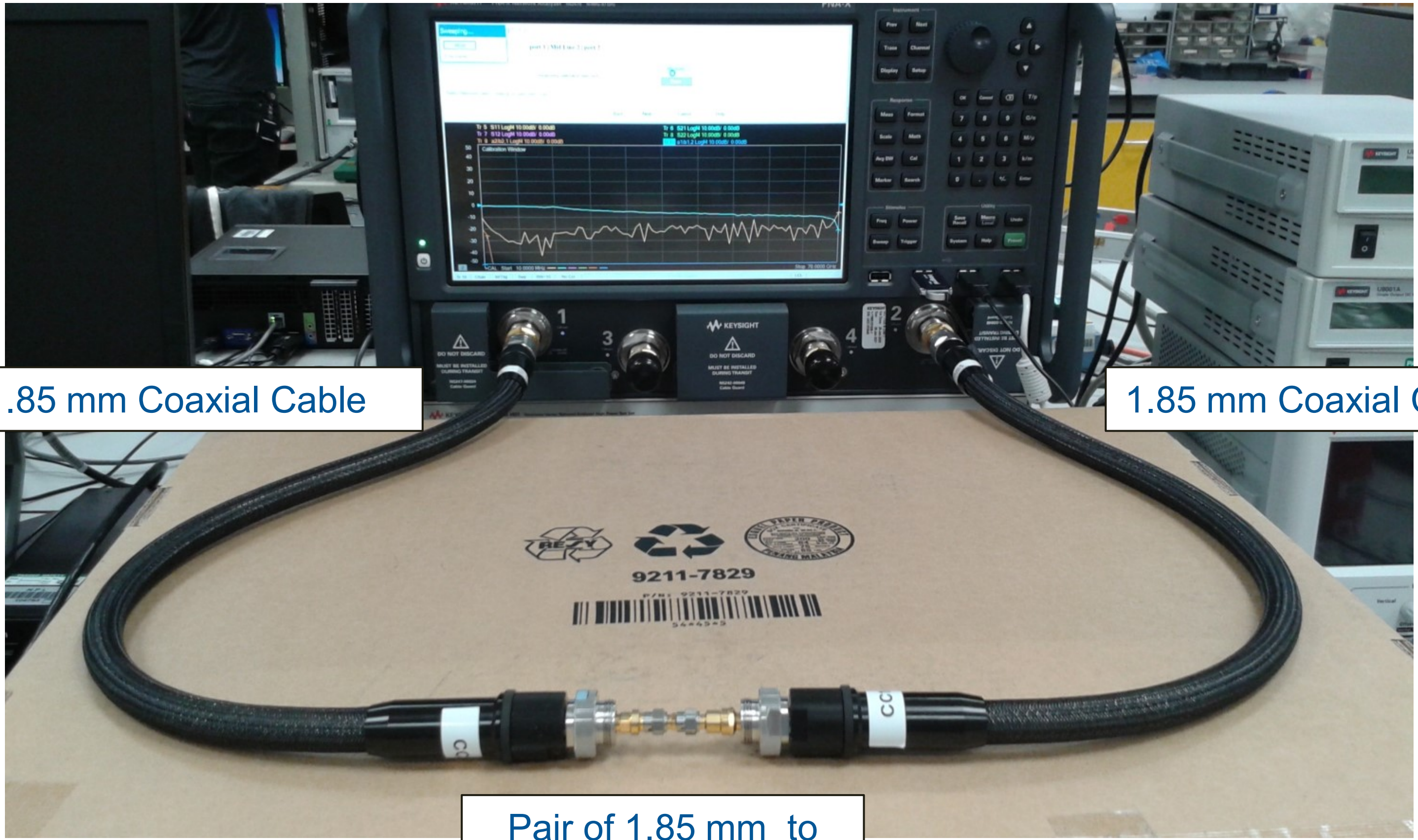
- VNA: Keysight N5274B PNA-X
- Port connectors: 1.85 mm – 67 GHz upper limit
- Frequency Extension: VDI Waveguide E-Band Extender heads - connected to PNA-X ports 1,2,3 & 4
- Adaptors: Rosenberger E-Band Waveguide to 1.35 mm coaxial adaptors (m & f)
- Frequency range: 60 to 90 GHz (band-limited)
- Additional setup required for measurement below 60 GHz – using 1.85 mm to 1.35 mm adaptors

1.35 mm Setup via E-Band Extender Heads



1.35 mm Setup via 1.85 mm Coaxial

1.85 mm Keysight PNA-X



1.85 mm Coaxial Cable

1.85 mm Coaxial Cable

Pair of 1.85 mm to 1.35 mm Coaxial Adaptors

Other Possible Cases

- 1.0 mm coaxial extension e.g. Keysight V3050A Signal Analyzer Frequency Extender

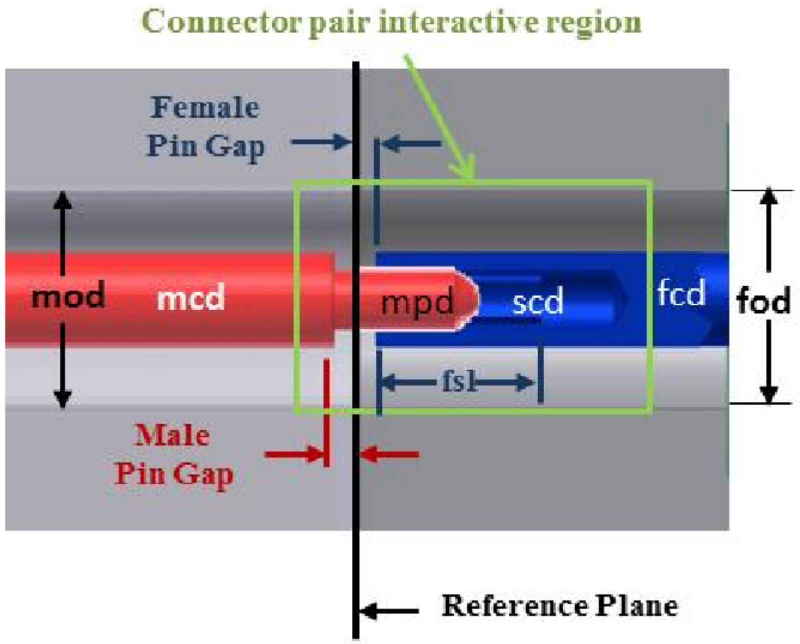
- Waveguide tapers e.g. W-Band Waveguide Extender Heads (75 – 110 GHz) + W-Band to E-Band waveguide tapers attached to ports

- And more…

Challenge: Uncertainty Analysis

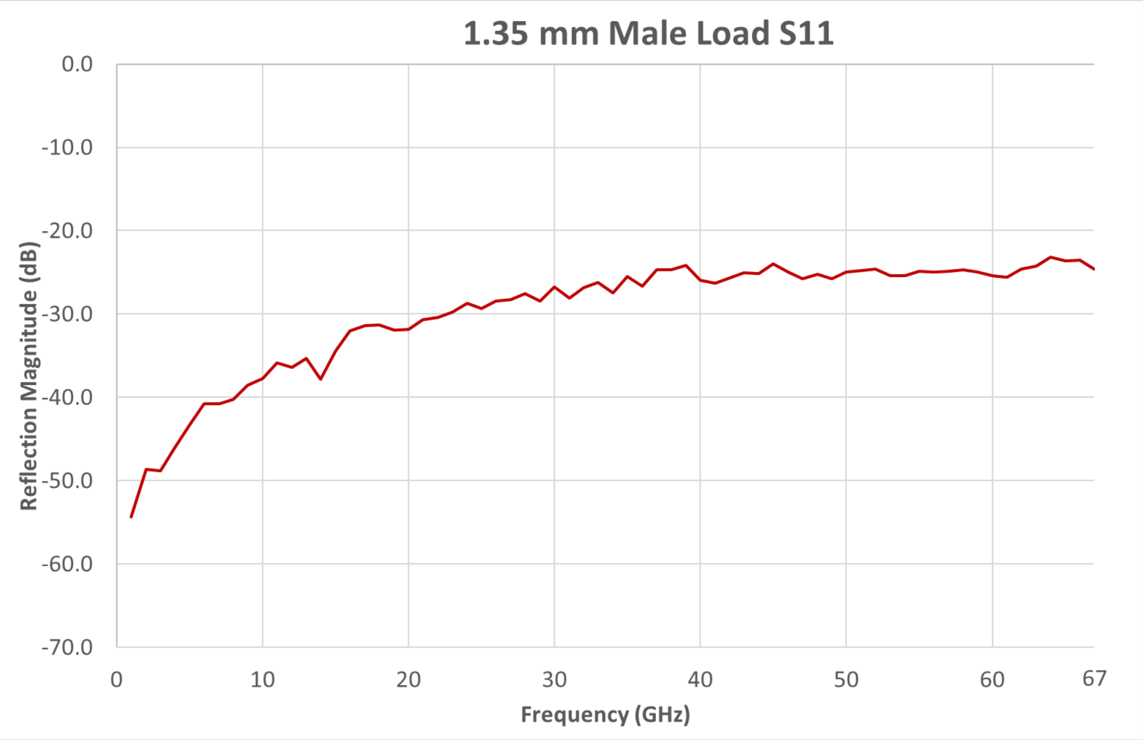
NPL National Physical Laboratory

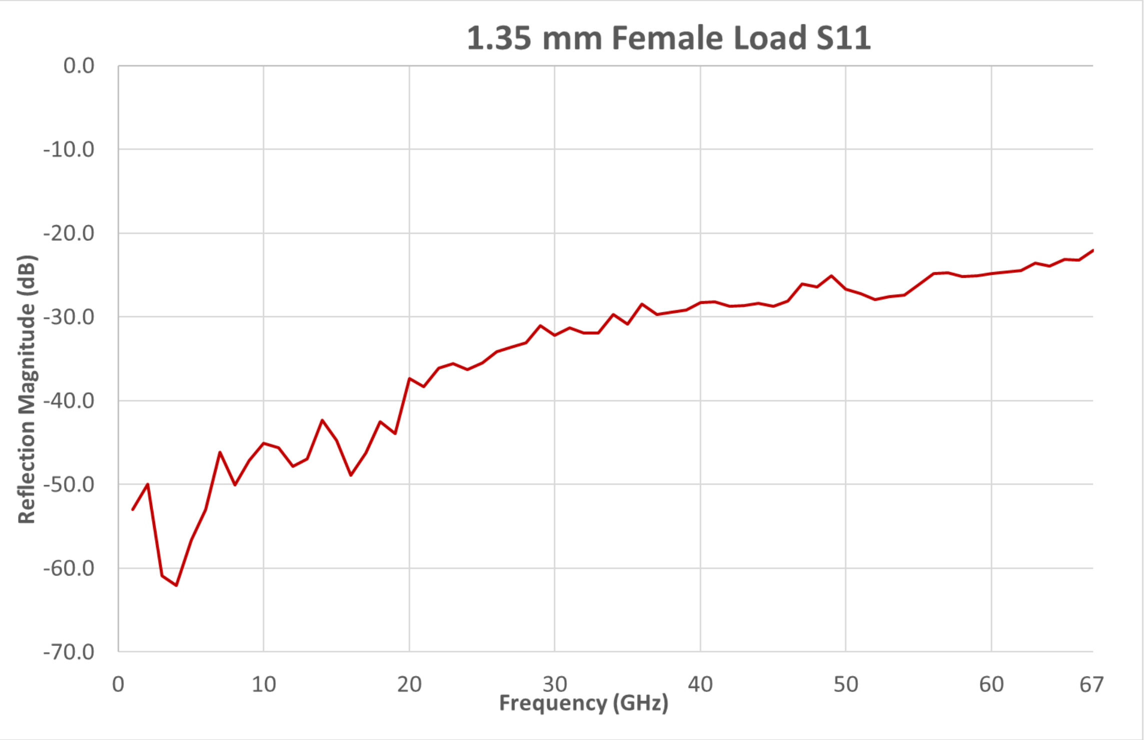
- Chief contribution: characterisation of calibration standards
- Understanding of connector effects – resonances at high frequencies caused by connector pin gaps



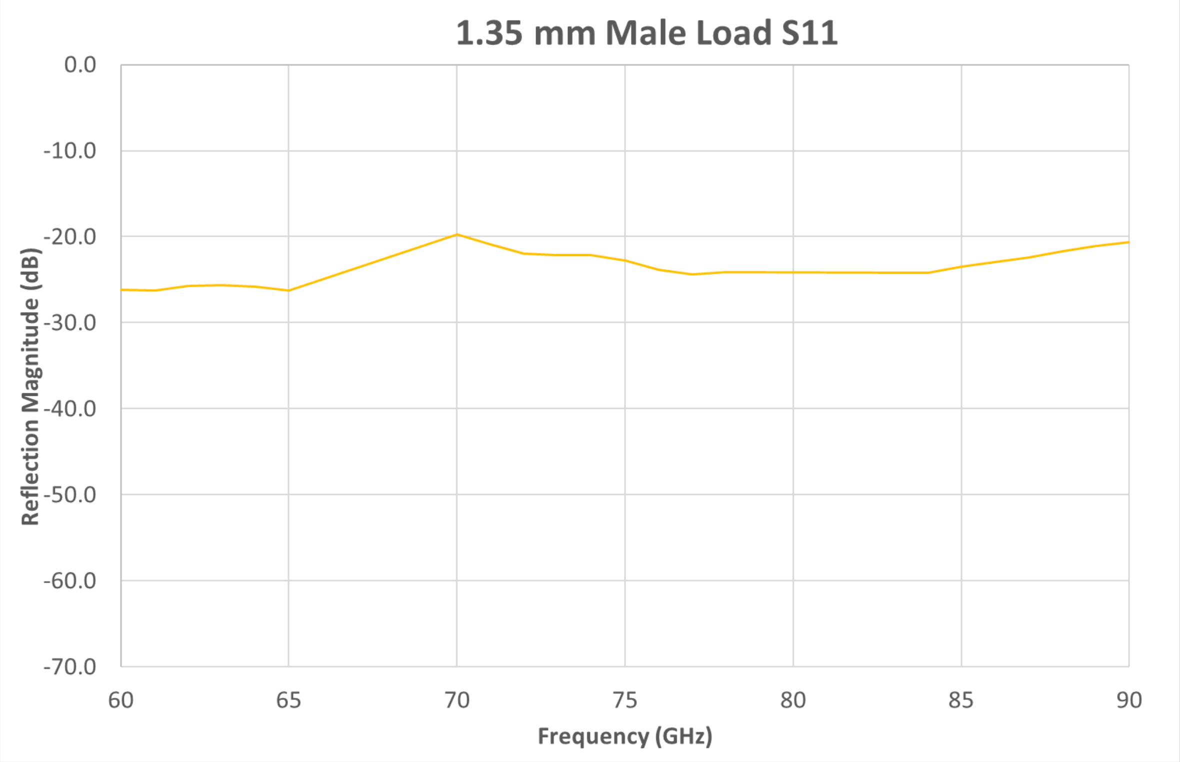
- Uncertainty Budget contributions:

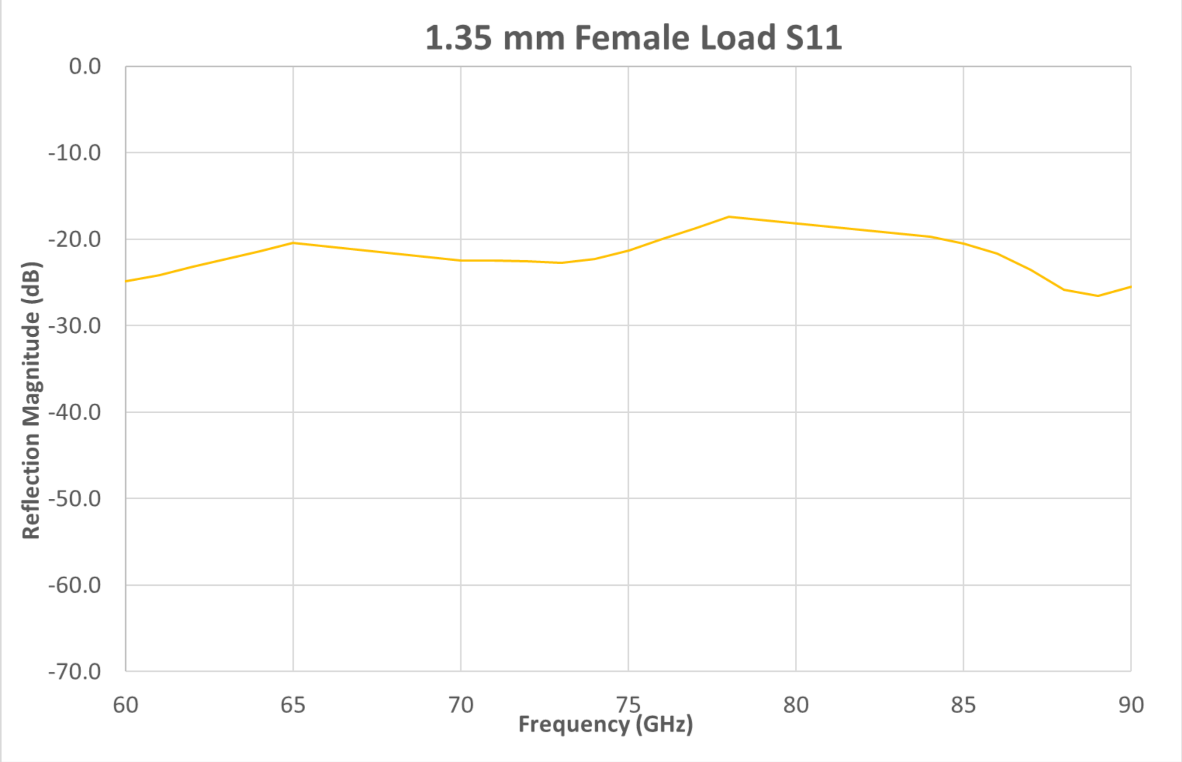
Results – Coaxial Setup via 1.85 mm Up to 67 GHz



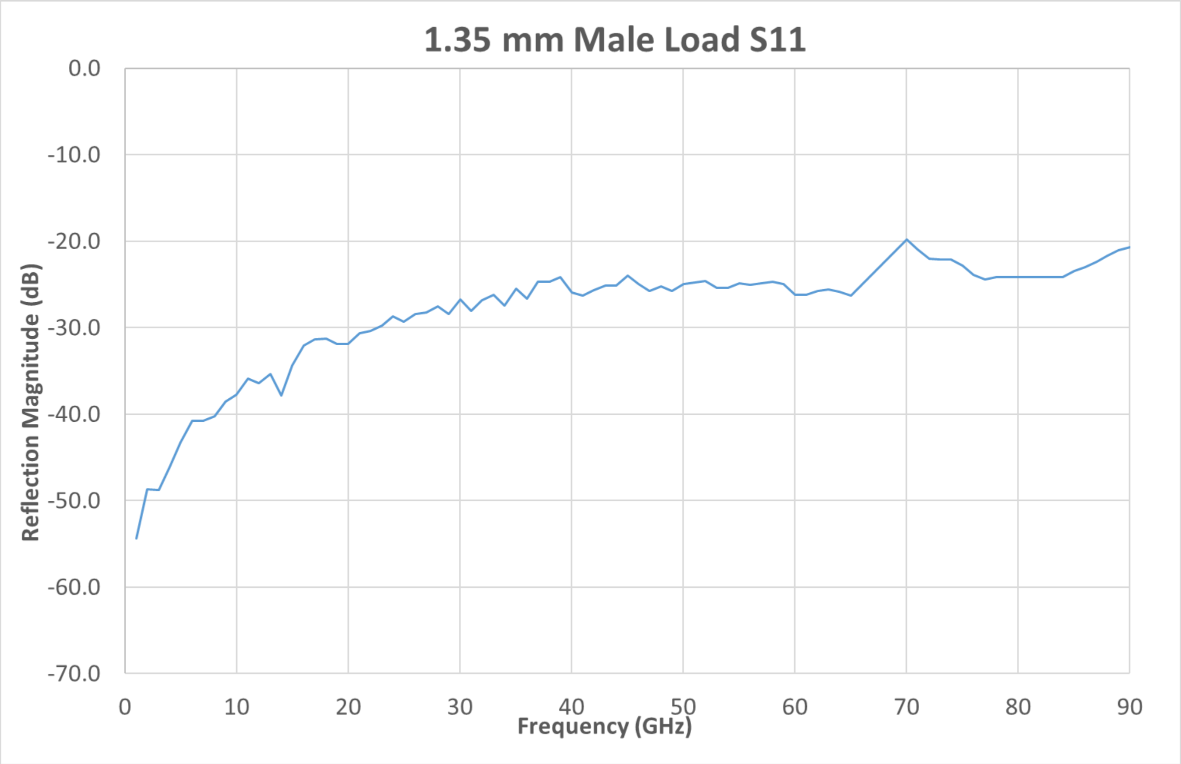


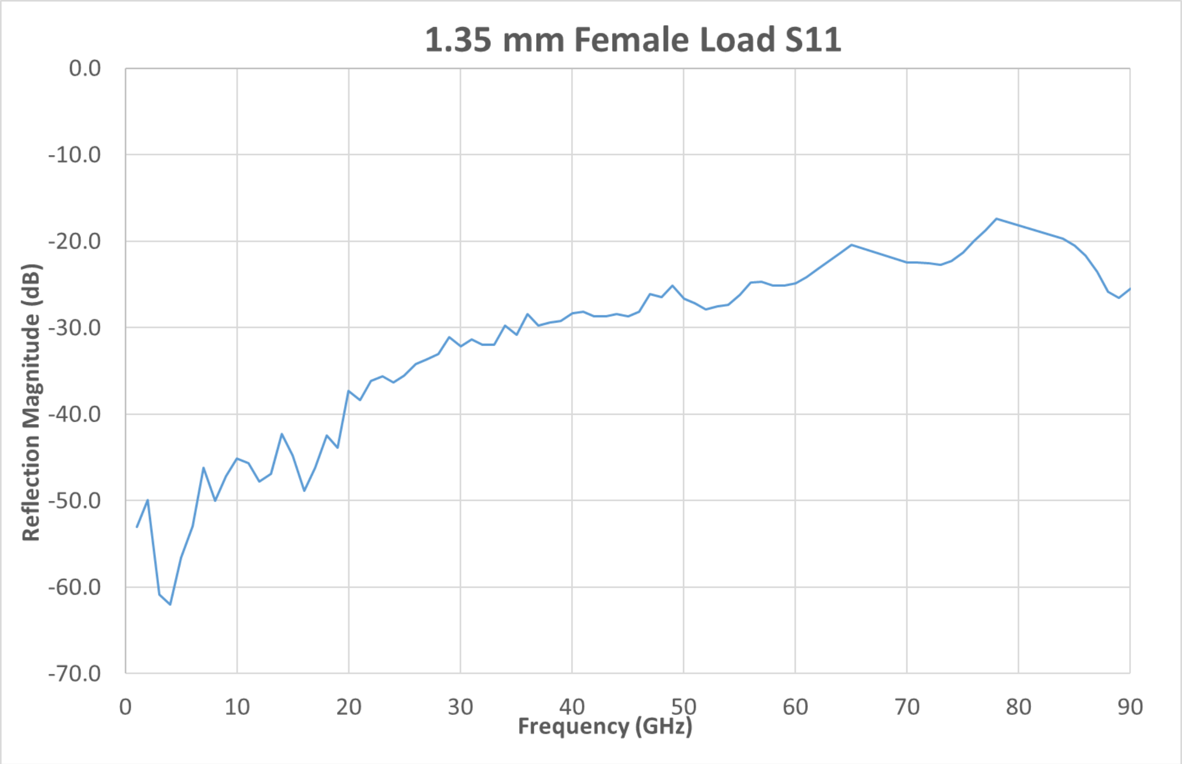
Results – Setup via E-Band Extender Heads 60 to 90 GHz





Combined Results





Next Steps

- Continue to develop measurement capability

- Dimensional intercomparison between project participants
  - In progress
  - Measurement of diameters of 1.35 mm airline inner conductor and outer conductor

- Electrical intercomparison between project participants
  - In progress
  - Calibration techniques
  - Methods of standard characterisation
  - Uncertainty analysis

Opportunities

- Provide s-parameter measurement services for 1.35 mm coaxial
- Establish power measurement capability for 1.35 mm power sensors
- Other measurement parameters

Thank You

Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

TEMMT-Workshop:

WP 2- Guidelines for the design of calibration substrates, including the suppression of parasitic modes, influence of microwave probes and crosstalk effects up to W-band

Gia Ngoc Phung, Uwe Arz, AG 2.23

Physikalisch-Technische Bundesanstalt,
Braunschweig, Germany

Outline

- Motivation:
  - On-Wafer Measurements
  - Method of Investigation
- Statement of Problem
- Influence of Microwave Probes
- Propagation and Suppression of Surface Waves
- Summary and Conclusion

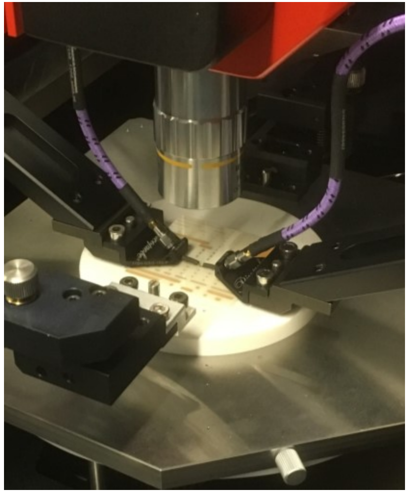
Motivation

On-Wafer Measurements (I)

- Main advantage: Characterization of any Device Under Test (DUT) without the influences of **packaging**

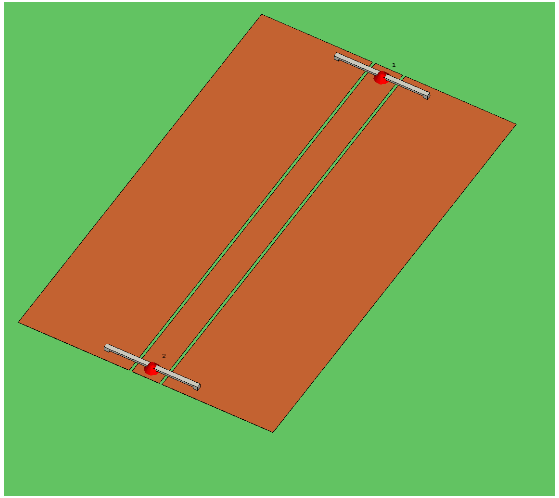
- Measurement performed with Ground Signal Ground (GSG) probes

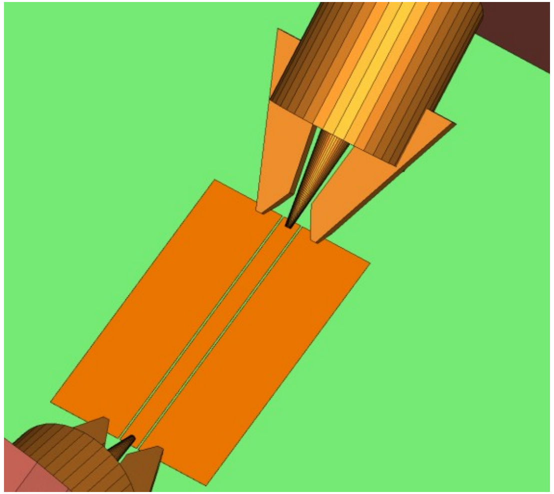
- Measured raw data contains parasitic effects of
  - the neighborhood
  - the probes
  - measurement instrumentation itself

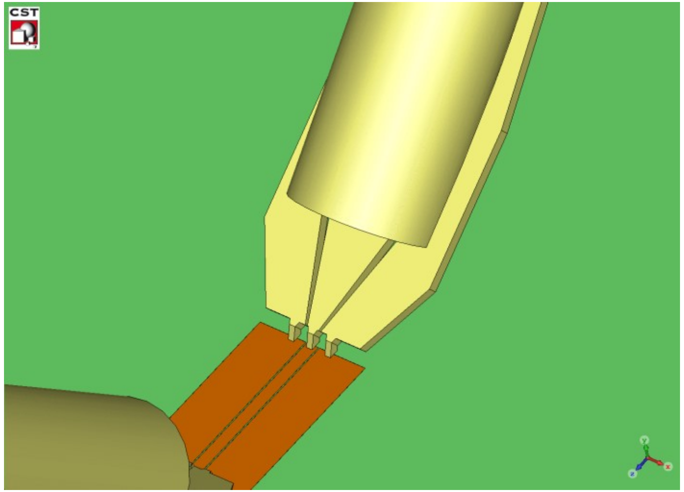


- How can we obtain the “true“ performance of any device ?
  - Applying a calibration process to deduct the unwanted effects from the raw data
  - Here, multiline Thru Reflect Line (mTRL) calibration applied

Method of Investigation: EM Simulation







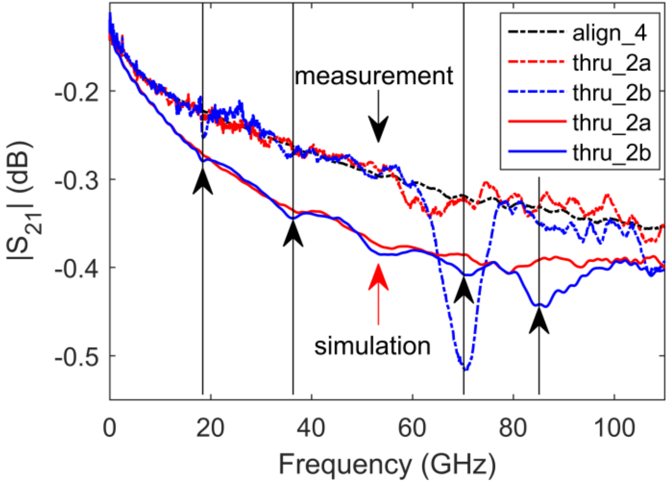
Bridge model
with least parasitics

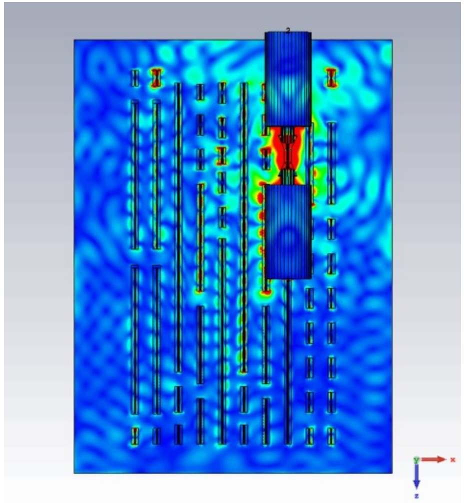
Probe model emulating measuring probes

Statement of Problem

Statement of Problem

- Several problems in on-wafer measurements detected but not clarified
- Focus of the talk:
  - **Influence of microwave probes**
  - **Influence of surface waves**





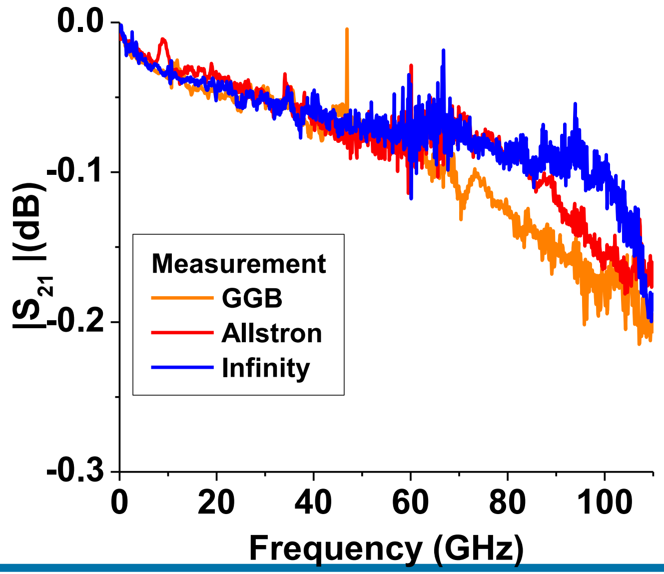
F.J. Schmückle, T. Probst, U. Arz, G.N. Phung, R. Doerner, and W. Heinrich, "Mutual Interference in Calibration Line Configurations," in 89th Automatic RF Techniques Group Microwave Measurement Conference (ARFTG) Digest, Honololu, HI, USA, Jun. 2017.

Influence of Microwave Probes

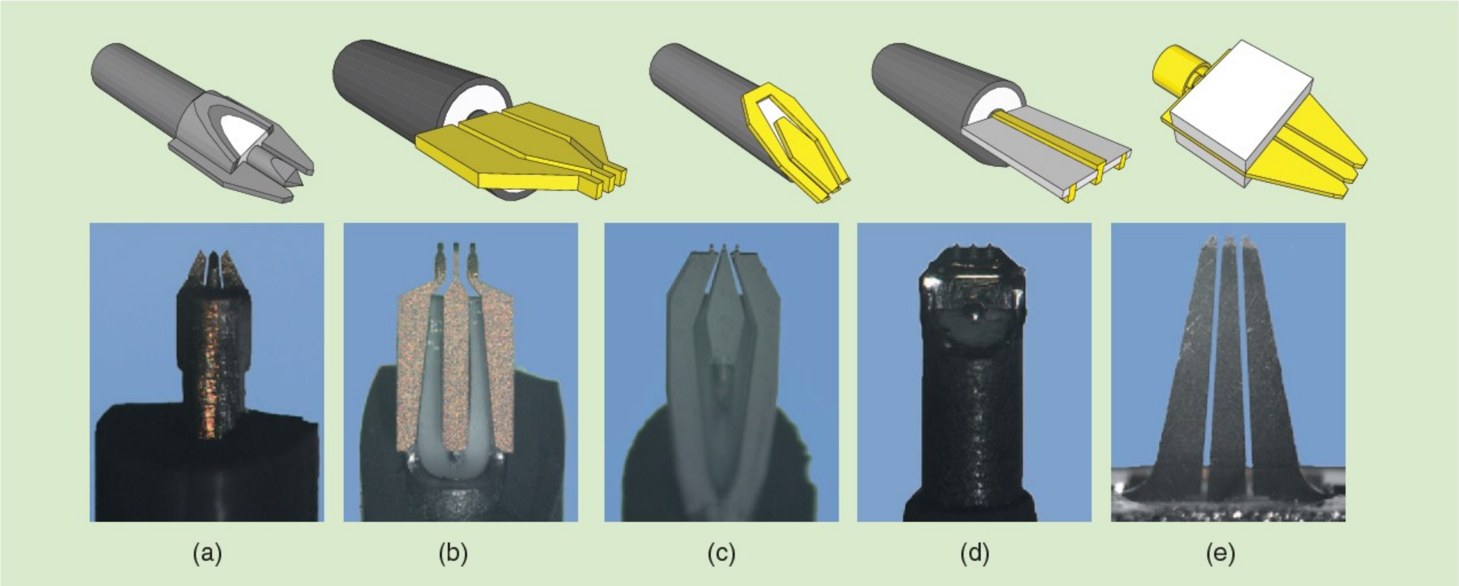
Starting Point of Investigation

- Different results of the same DUT measured with
- different probes from different manufacturers
  - GGB
  - Allstron
  - Infinity

Which measurement shows the true performance of the DUT, if any ?



Probes from different manufacturers

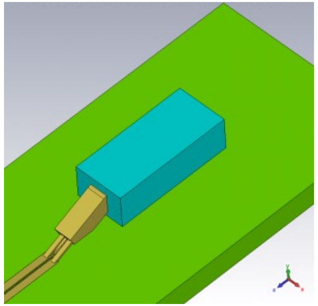


(a) Picoprobe (top view, 100-µm pitch), (b) ACP (125-µm pitch), (c) Allstron (100-µm pitch), (d) Infinity Probe (125-µm pitch; all bottom view), and (e) |Z| Probe (125-µm pitch).

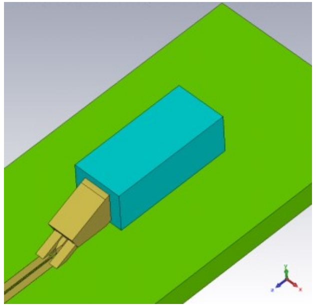
[3] Rumiantsev, Andrej and R. Doerner. “RF Probe Technology: History and Selected Topics.” IEEE Microwave Magazine 14 (2013): 46-58.

Parasitic Effects : Systematic Study of Influence of Microwave Probes

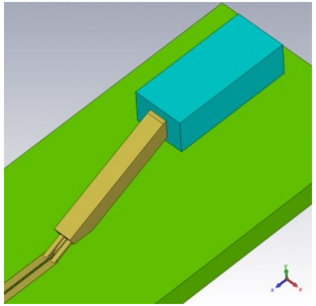
- Simulation environment remains the same for all the calibration elements and DUTs
- Construction of a probe prototype
  - Exaggeration of the probe geometries in order to observe pronounced effects
  - Parametrization of the investigated probe geometries (length, slant and angle of probe)
  - Scaling of the cross-section of the probe



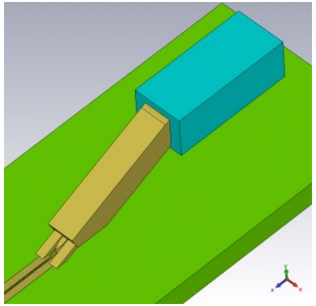
Probe 1.1



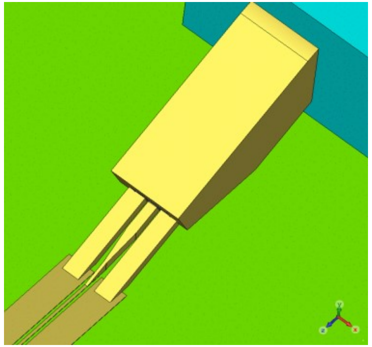
Probe 2.1

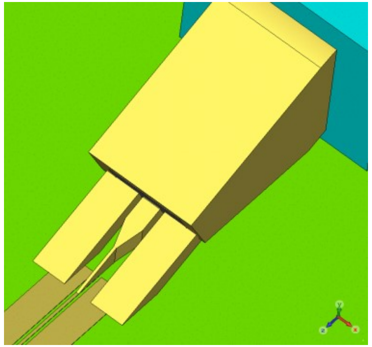


Probe 1.2

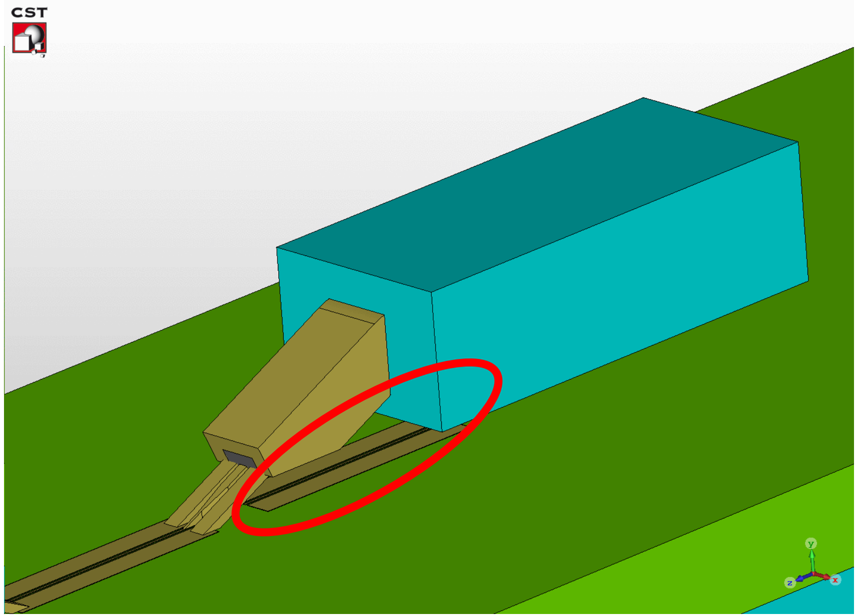


Probe 2.2





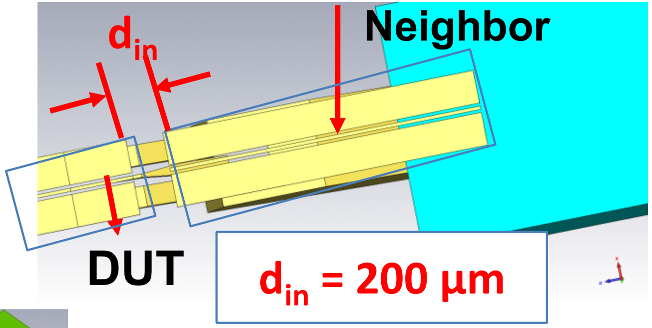
Structure under Probe Region

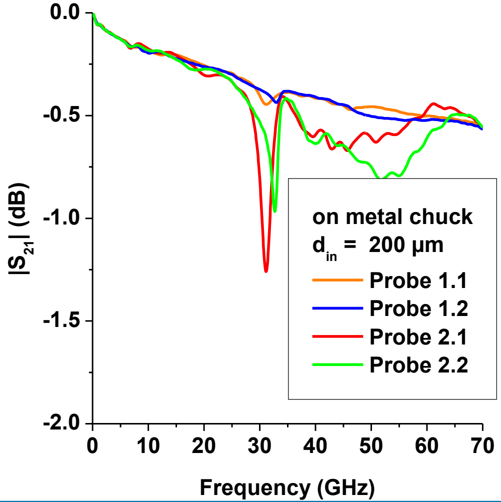


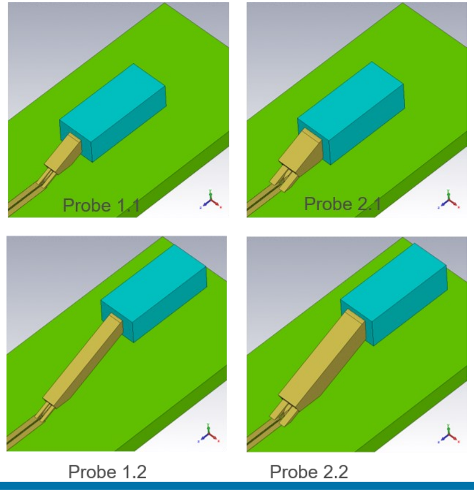
Structure
underneath
the probe shadow

Parasitic Effects : Neighbor in Probe Region (I)

- On metal chuck
  - For distance d_{in} = 200 µm
  - Strength of resonance varies with probes

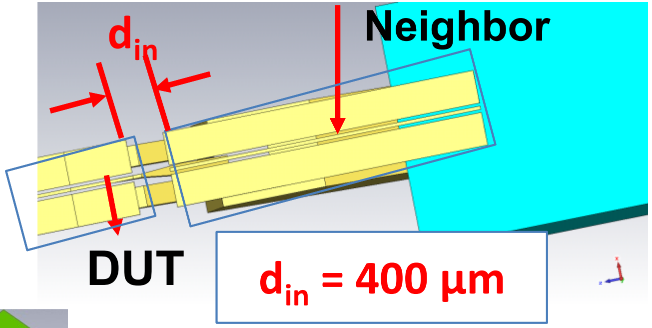


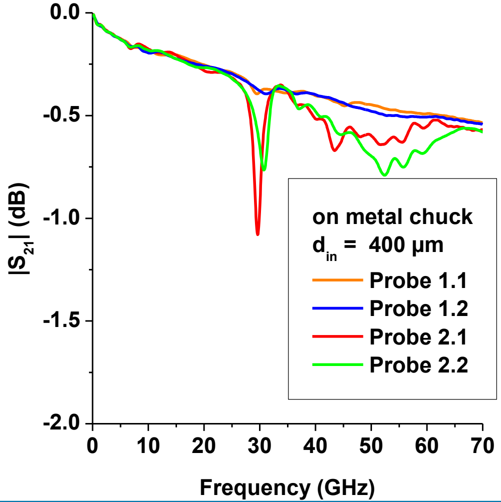


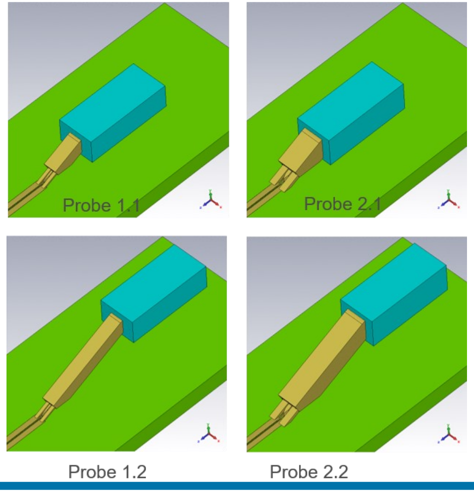


Parasitic Effects : Neighbor in Probe Region (II)

- On metal chuck
  - For distance d_{in} = 400 µm
  - Strength of resonance varies with probes

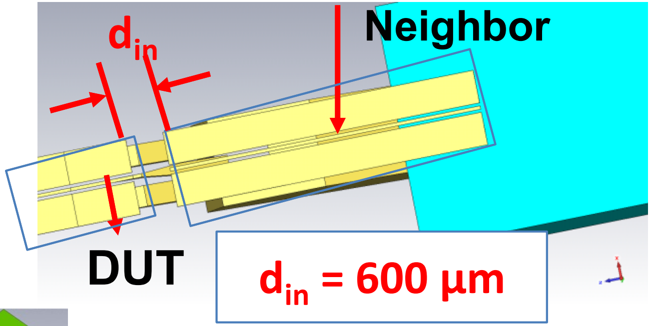


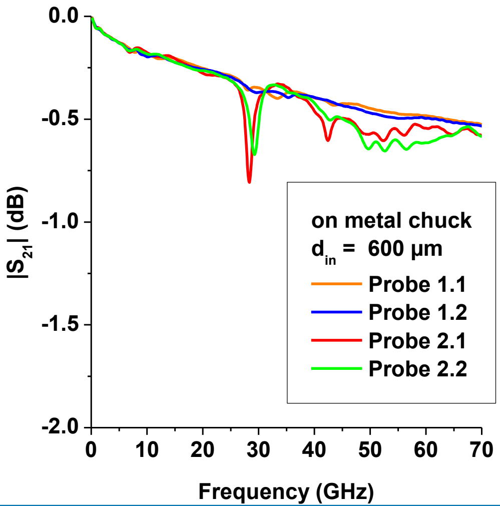


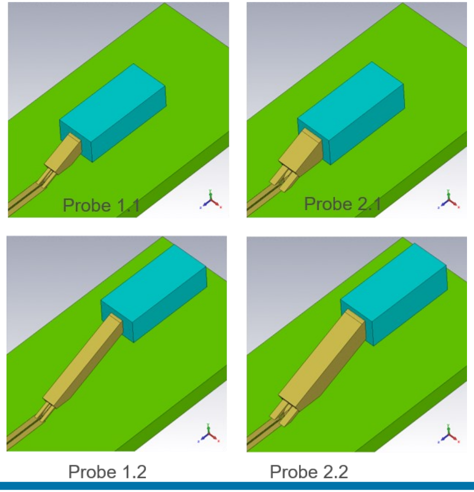


Parasitic Effects : Neighbor in Probe Region (III)

- On metal chuck
  - For distance d_{in} = 600 µm
  - Strength of resonance varies with probes

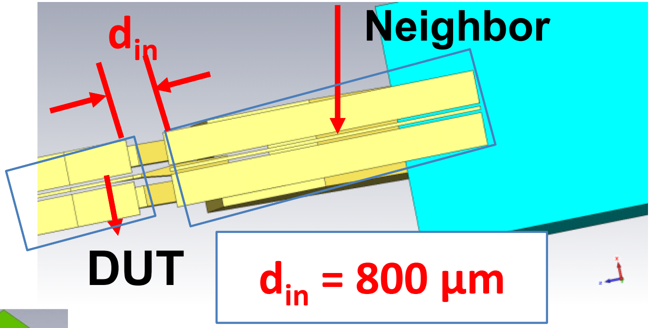


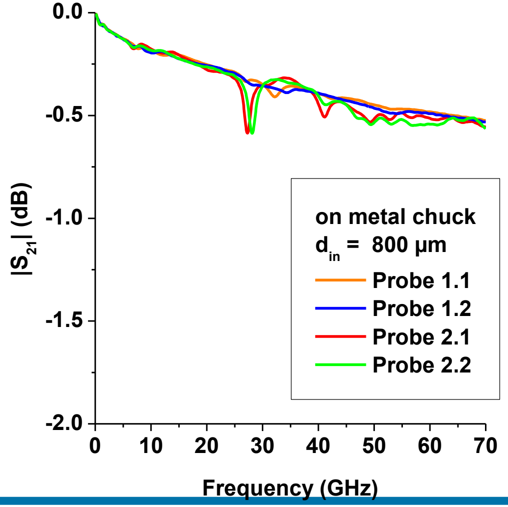


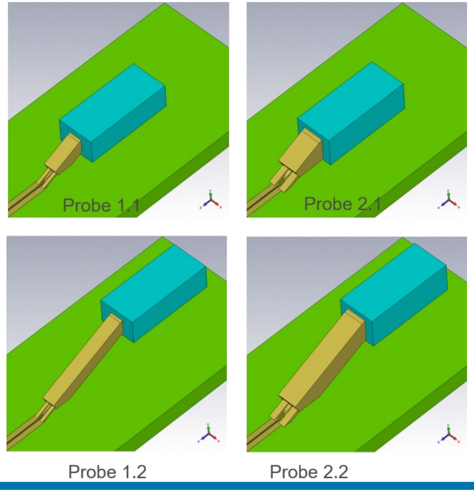


Parasitic Effects : Neighbor in Probe Region (IV)

- On metal chuck
  - For distance d_{in} = 800 µm
  - Strength of resonance varies with probes

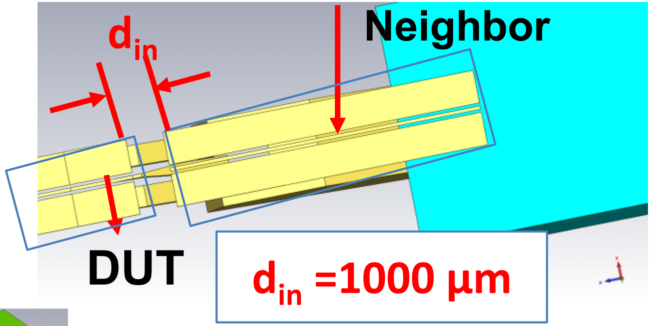


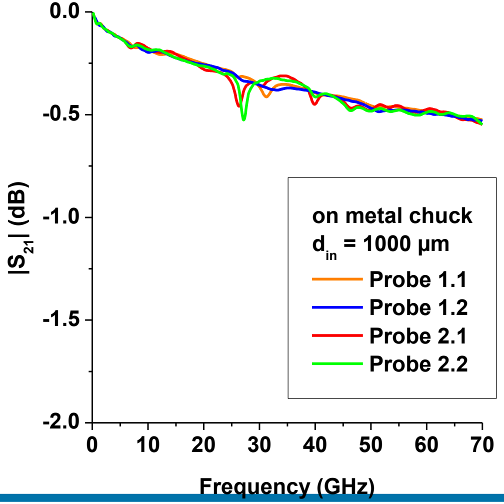


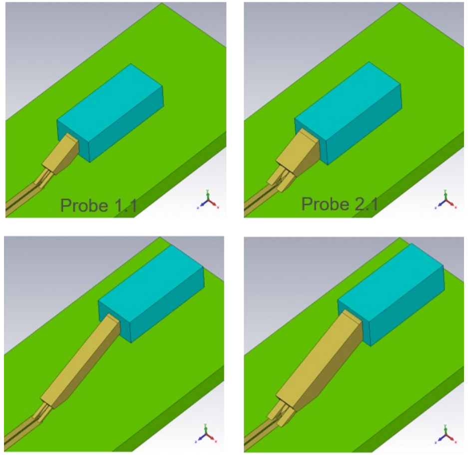


Parasitic Effects : Neighbor in Probe Region (V)

- On metal chuck
  - For distance d_{in} = 1000 µm
  - Strength of resonance varies with probes

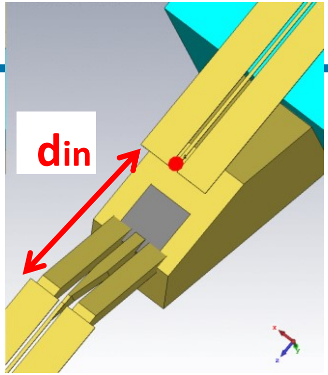




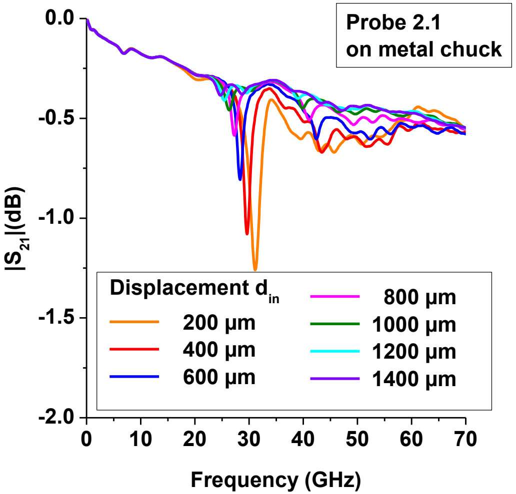


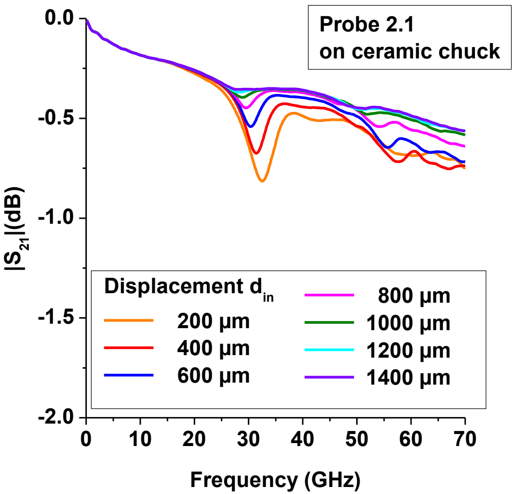
Probe 1.2 Probe 2.2

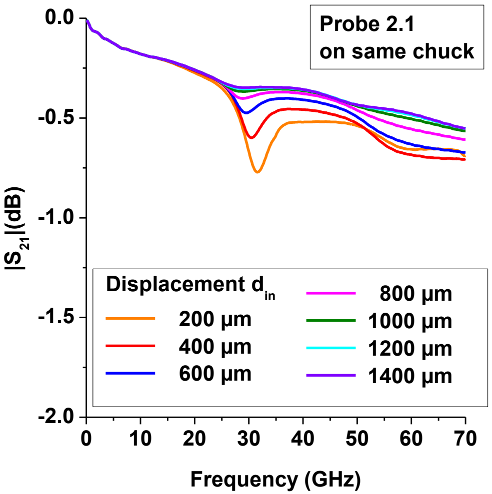
Impact of Chuck Material



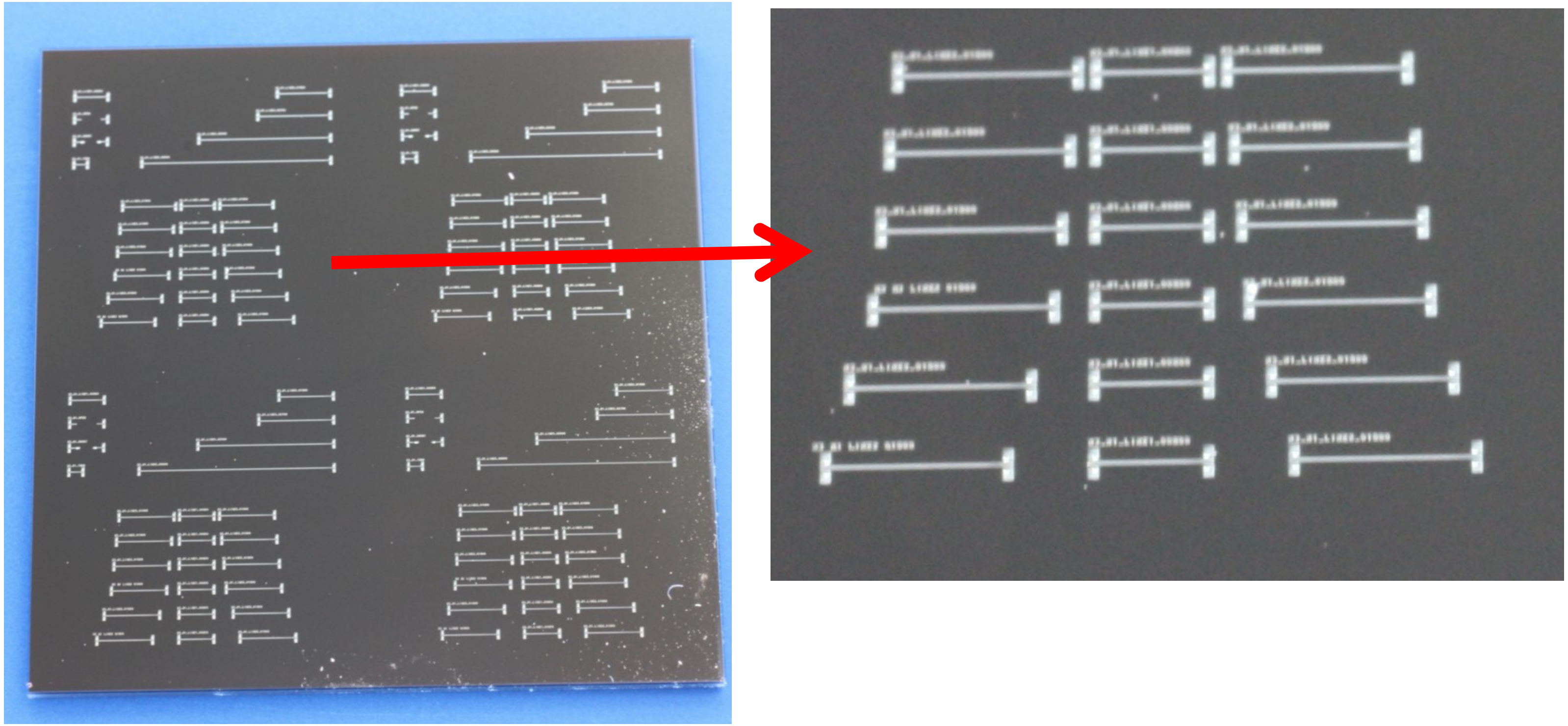
- Neighbor in probe region: DUT on different chuck material
  - Distance d_{in} varies from 200 till 1400 µm
  - The larger the distance, the weaker the resonance.
  - Chuck material influences the strength of the resonance



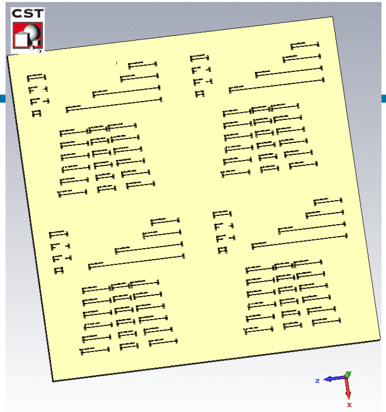




Verification through Measurements

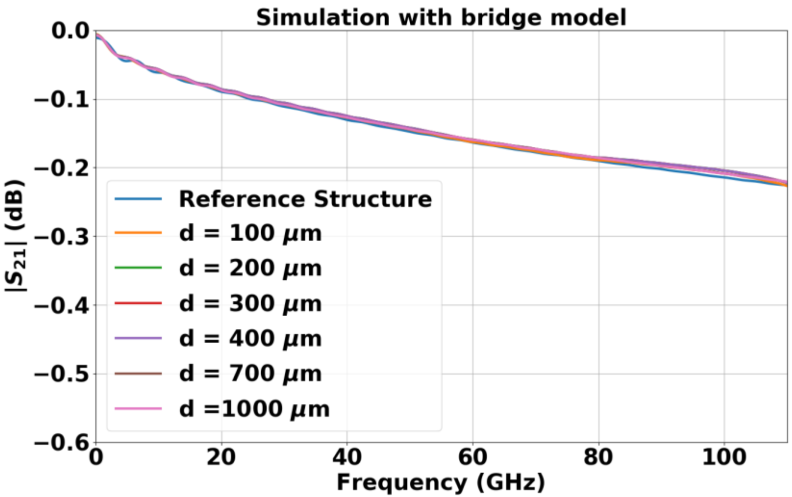


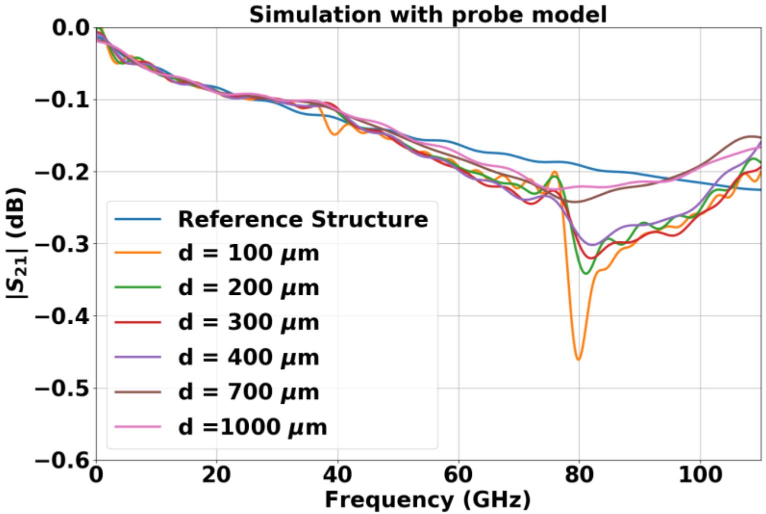
Simulation of Layout Design



Simulation of complete wafer with different excitations

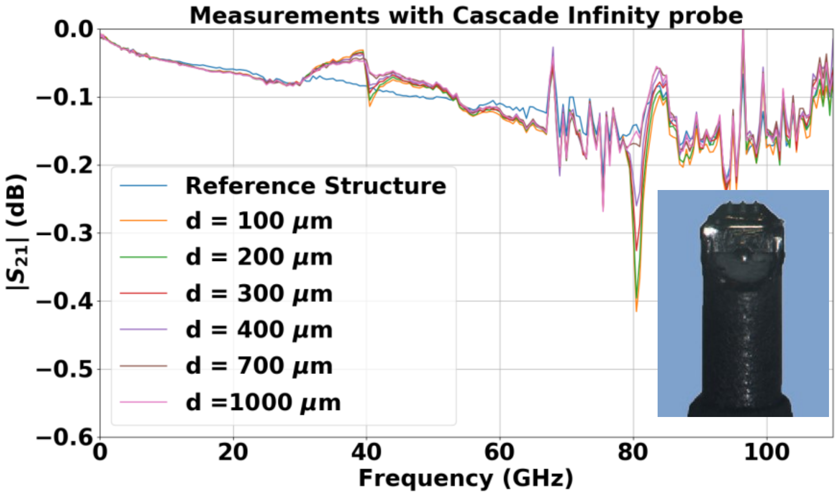
- Smooth curve behavior with simplified bridge model
- Bridge model is too ideal to describe reality
- Resonant effects with probe simulation

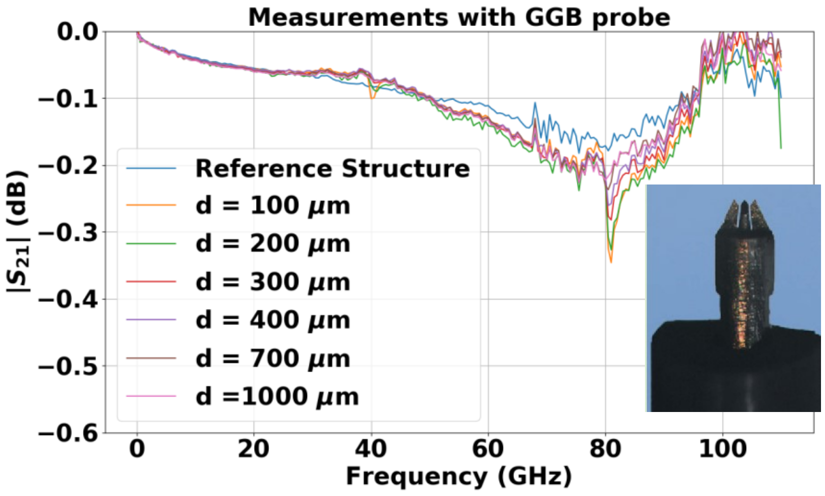




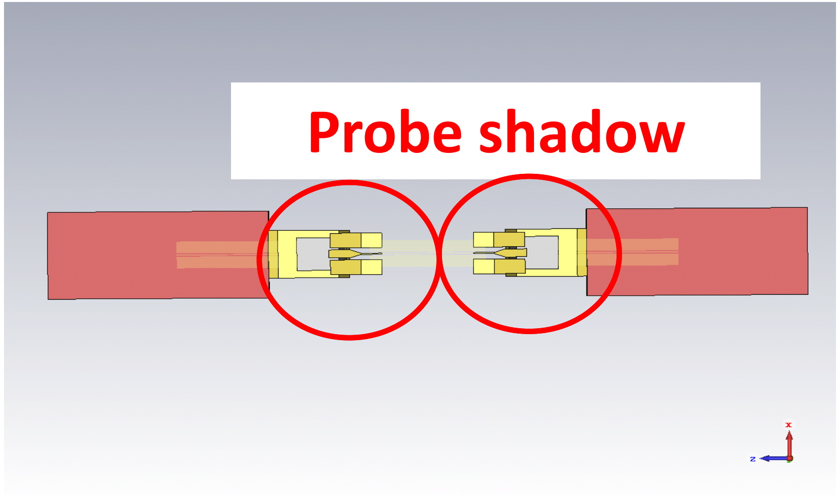
Measurement Results

- Probes from different manufacturers show different shape and deviations at the peak, due to the different probe geometries as predicted in simulations.



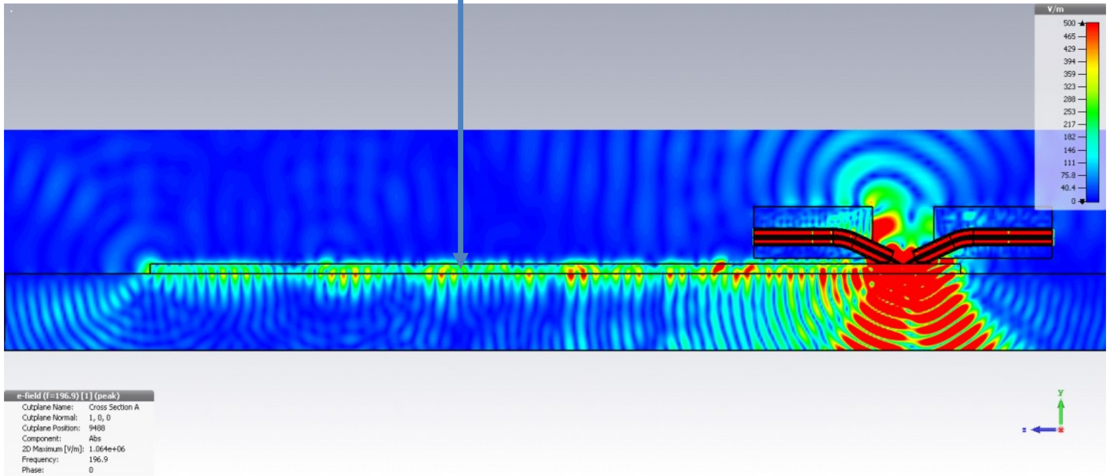


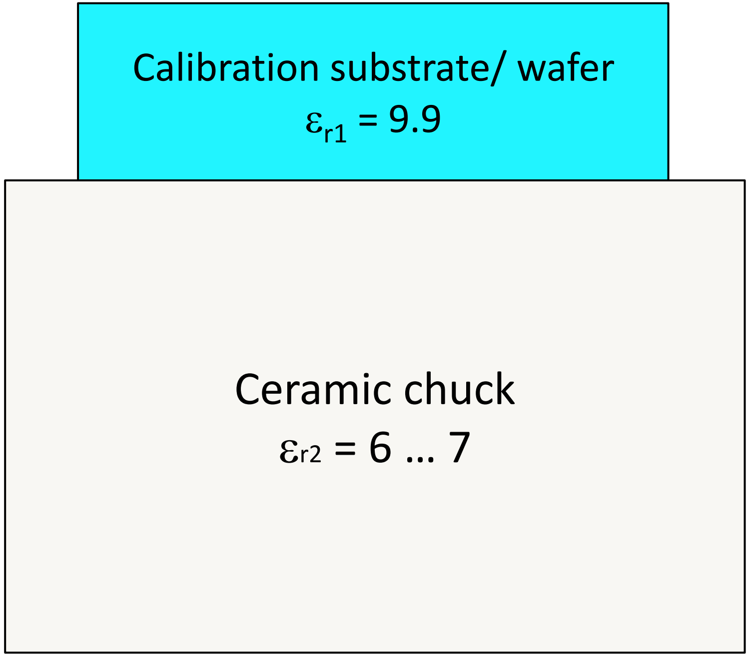
- **Keep the sensitive regions of the probe shadow free of structures to avoid probe coupling to neighboring structure!!!**



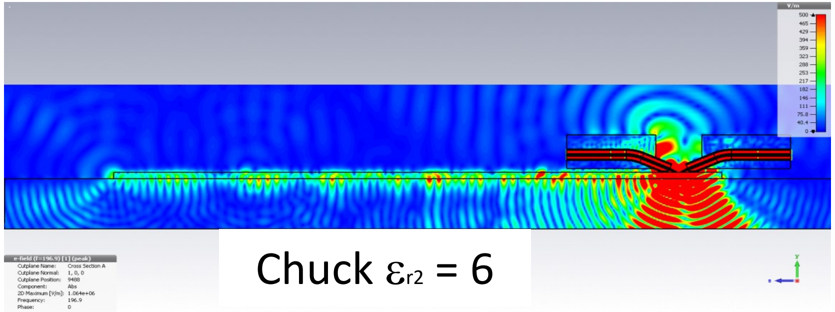
- **Influence of Surface Waves**

Propagation of surface waves in multilayered stackup due to $\varepsilon_{r1} > \varepsilon_{r2}$

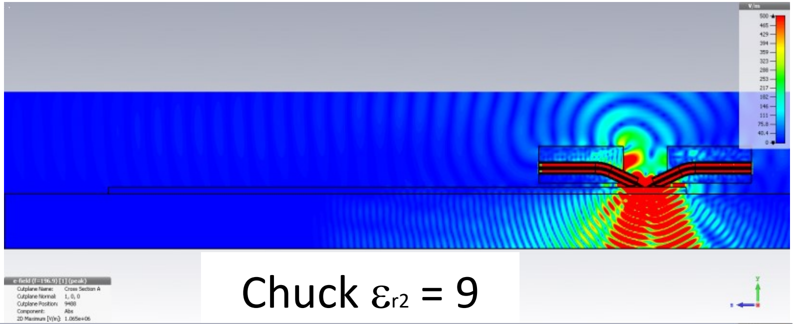




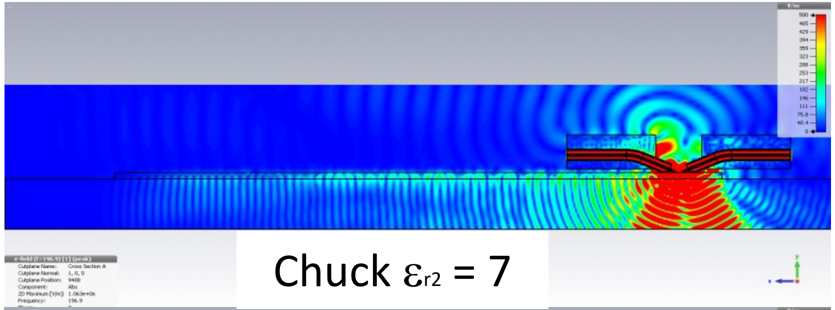
Influence of Chuck Permittivity



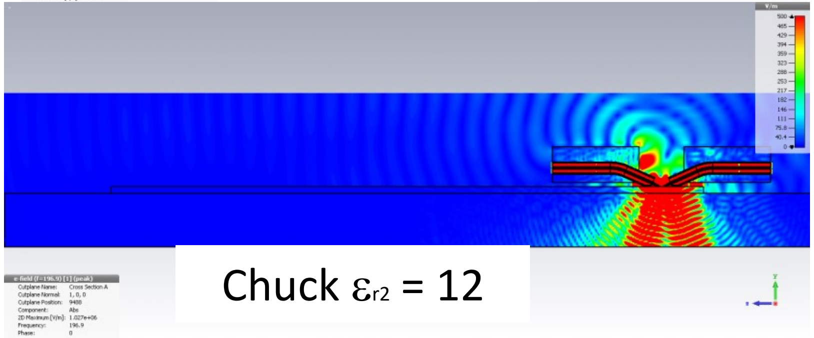
Chuck ε_{r2} = 6



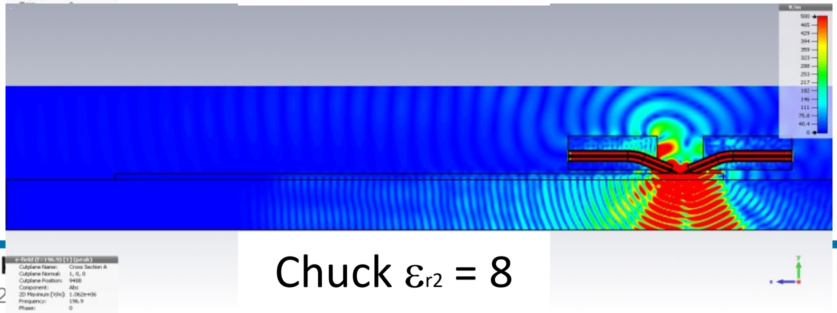
Chuck ε_{r2} = 9



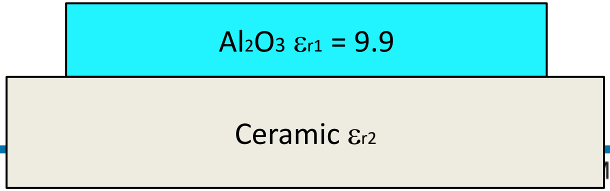
Chuck ε_{r2} = 7



Chuck ε_{r2} = 12



Chuck ε_{r2} = 8



Design Guideline: Surface Waves

Guideline 1: Use a thin substrate or one with low dielectric constant → Shifts the cut-off frequency of the surface waves upwards

Or

Guideline 2: Use a chuck with the same dielectric constant as the wafer or above

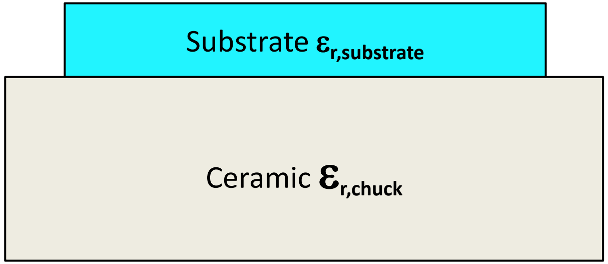
$\varepsilon_{r,chuck} \sim \varepsilon_{r,substrate}$ or $\varepsilon_{r,chuck} > \varepsilon_{r,substrate}$

- **Validation of the Design Guideline for Surface Waves by Measurements**

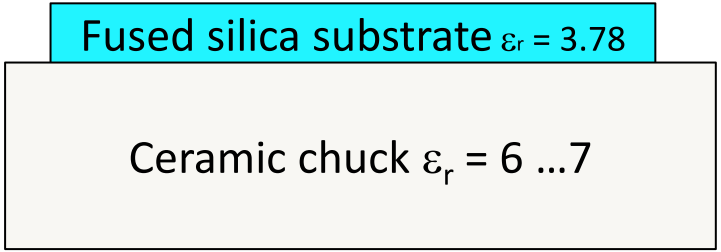
Design Guidelines for Chuck Boundary Conditions

Use a chuck with a dielectric constant similar or higher than that of the substrate

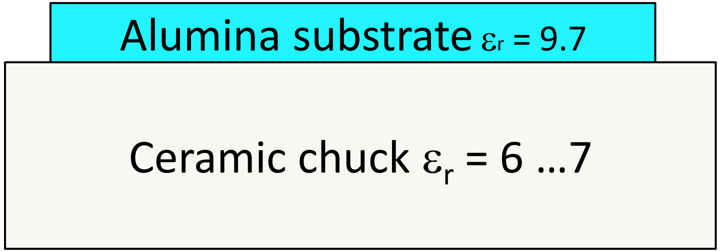
$\varepsilon_{r,chuck} \sim \varepsilon_{r,substrate}$ or $\varepsilon_{r,chuck} > \varepsilon_{r,substrate}$



M. Spirito, U. Arz, G. N. Phung, F. J. Schmückle, W. Heinrich,and R. Lozar, “Guidelines for the Design of Calibration Substrates, including the Suppression of Parasitic Modes for Frequencies up to and including 325 GHz,” EMPIR 14IND02 – PlanarCal, 2018, Physikalisch-Technische Bundesanstalt (PTB), 2018.



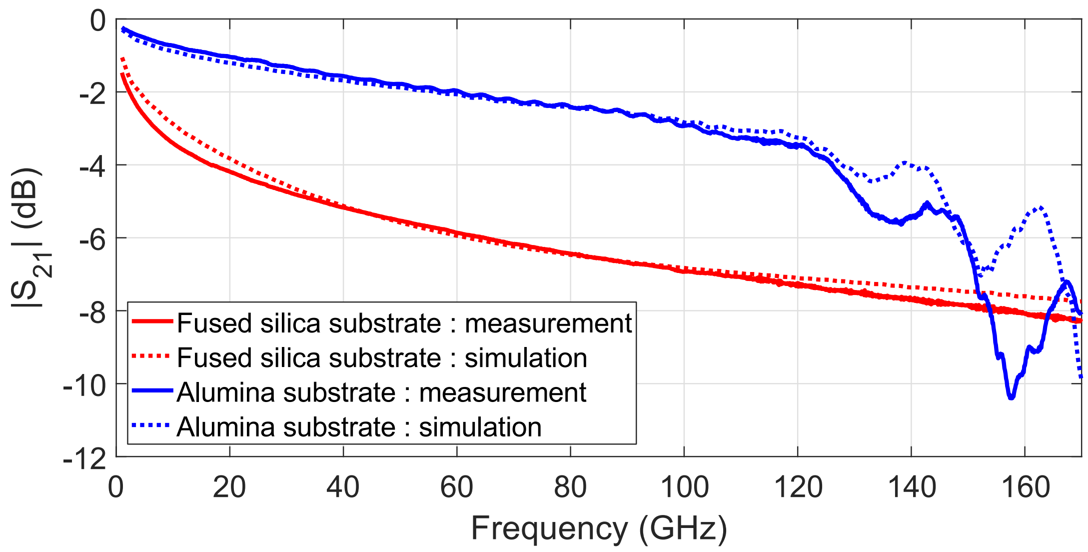
No surface wave expected



Surface wave expected

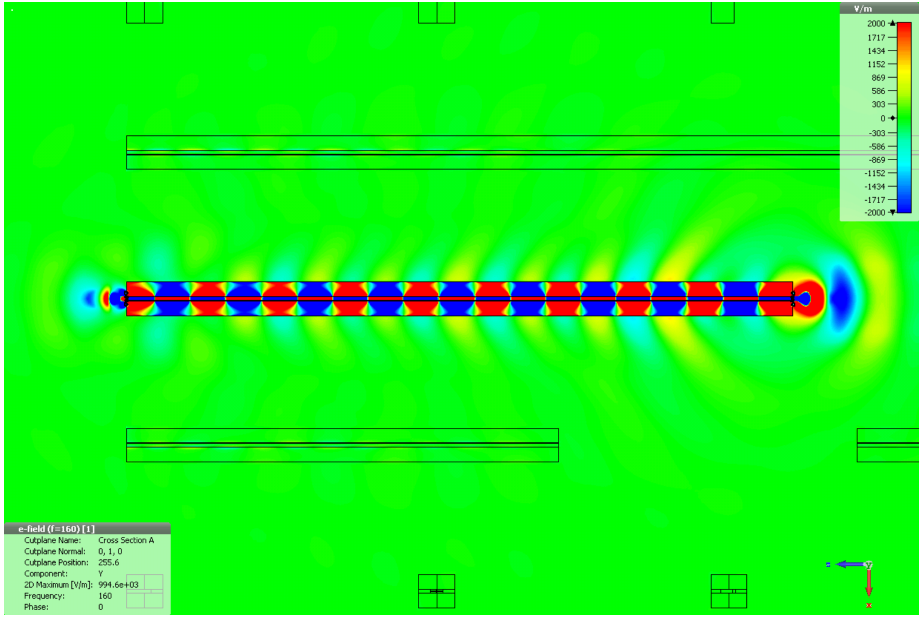
Impact of Surface Waves

- Selected DUT l = 11400 µm to avoid probe coupling btw. the needles
- Fused silica: smoother transmission behavior
- Alumina substrate: more peculiarities and a strong resonance near 160 GHz.



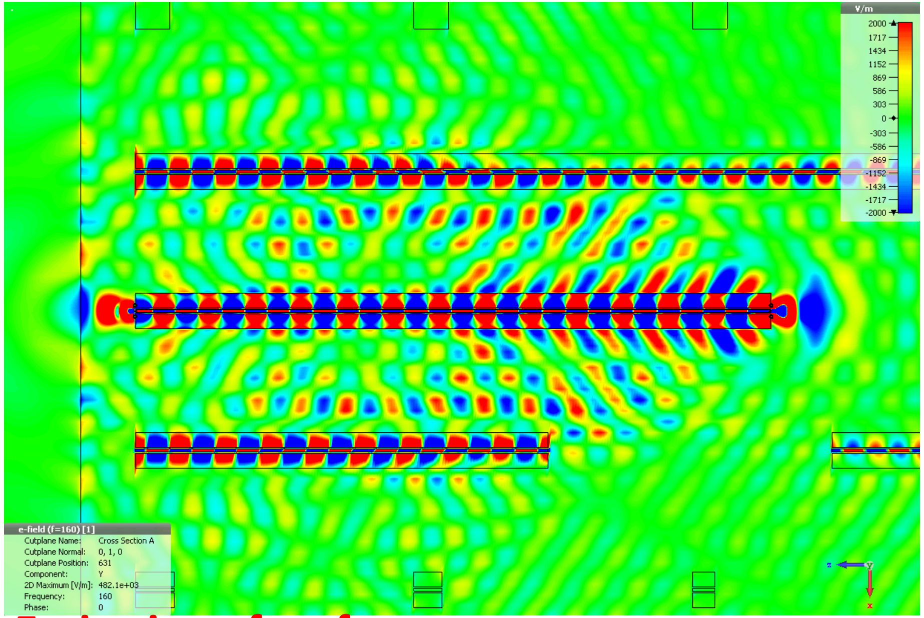
Impact of Surface Waves

Fused silica substrate ε_r = 3.78



Less parasitics

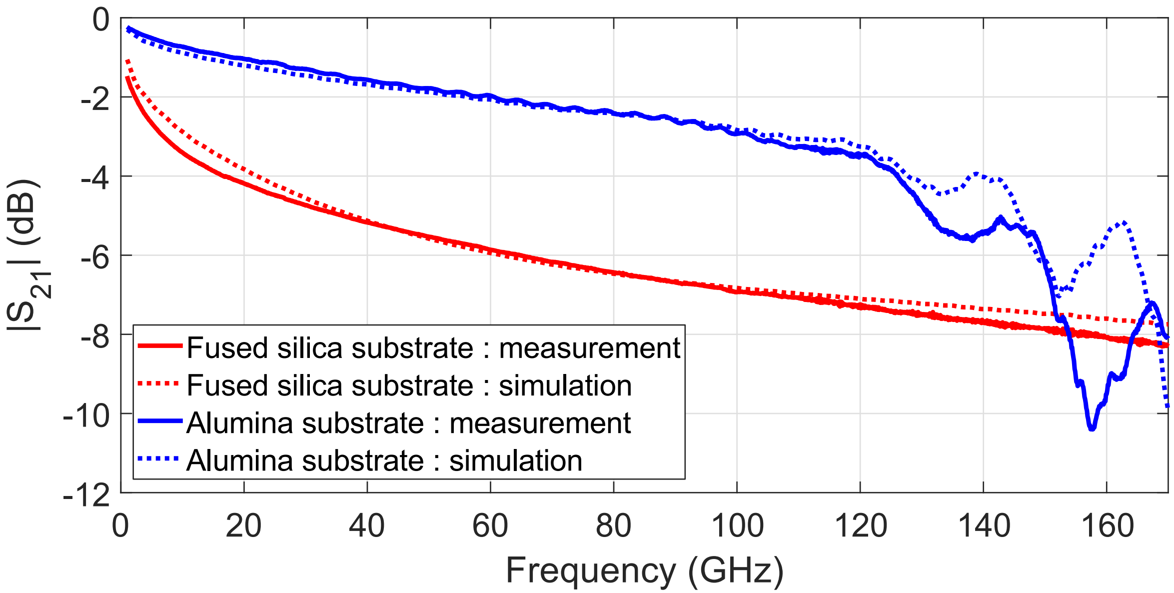
Alumina substrate ε_r = 9.7



- Excitation of surface waves
- Coupling to neighboring lines and excitation of the slotline modes there

Impact of Surface Waves

→ Smooth curve behavior for fused silica case

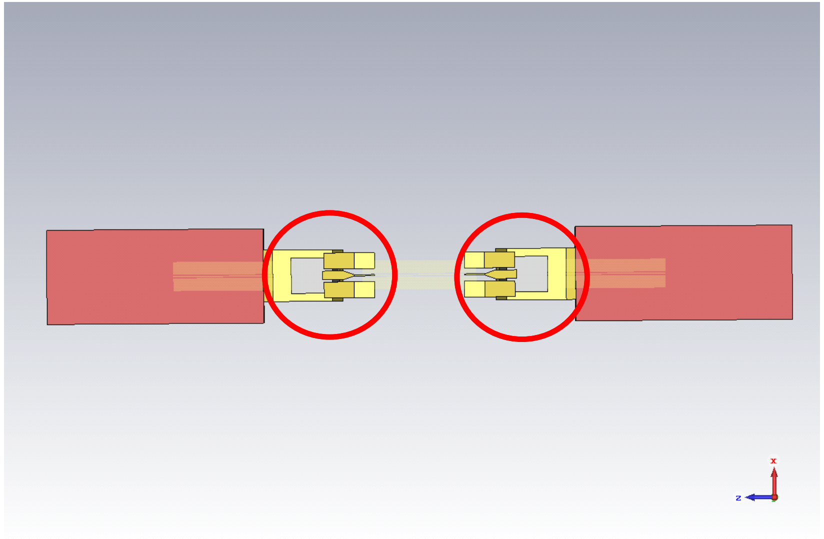


Verification of the guideline for surface waves

Summary and Conclusion

Summary of Guidelines

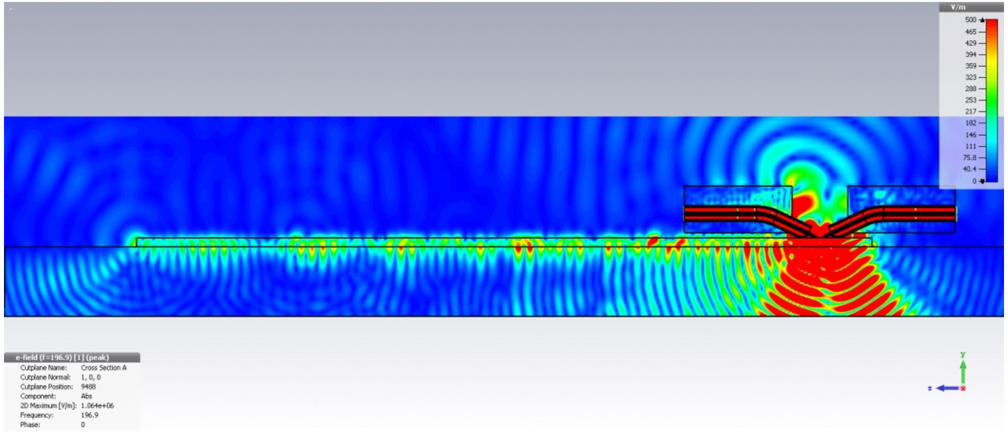
- **Guideline:** Influence of Microwave Probes
  - Keep the sensitive regions under the probe free of structures



Summary of Guidelines

- **Guideline: Influence of Surface Waves**
  - Use a thin wafer or one with low dielectric constant to shift the cut-off frequency of the surface waves upwards
  - Use a chuck with the same dielectric constant as the wafer or above

    $\varepsilon_{r,chuck} \sim \varepsilon_{r,substrate}$ or $\varepsilon_{r,chuck} > \varepsilon_{r,substrate}$



Acknowledgment

Acknowledgment

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Both projects (14IND02 and 18SIB09) have received funding from the EMPIR programme co-financed by the Participating States

and from the European Union's Horizon 2020 research and innovation programme.

Thanks

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  - Dirk Schubert
- FBH:
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  - Franz-Josef Schmückle
  - Ralf Doerner

Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
Bundesallee 100
38116 Braunschweig

Gia Ngoc Phung
Telefon: 0531 592-2226
E-Mail: gia.phung@ptb.de
www.ptb.de

Nano-robotic on-wafer probe station under scanning electron microscope

Kamel HADDADI

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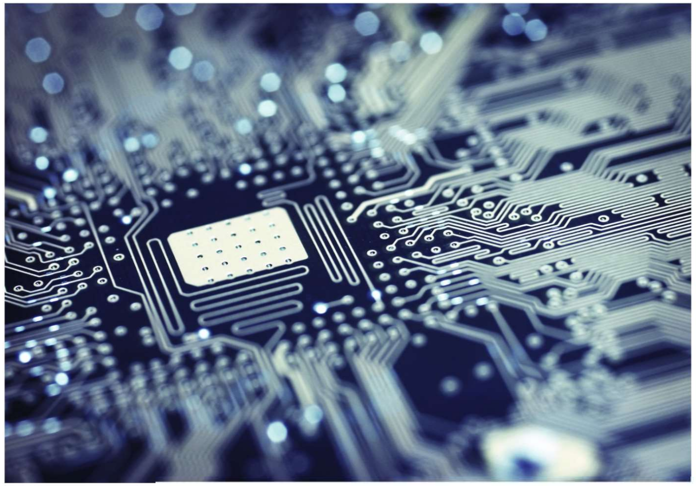
UMR CNRS 8520

kamel.haddadi@univ-lille.fr

1st TEMMT Training Course

Microwave measurements for planar circuits and components

Short Name: PlanarCal, Project Number: 14IND02



Circuit Board - Space

http://planarcal.ptb.de/

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JRP SRT- EMPIR PlanarCal 2015-2018

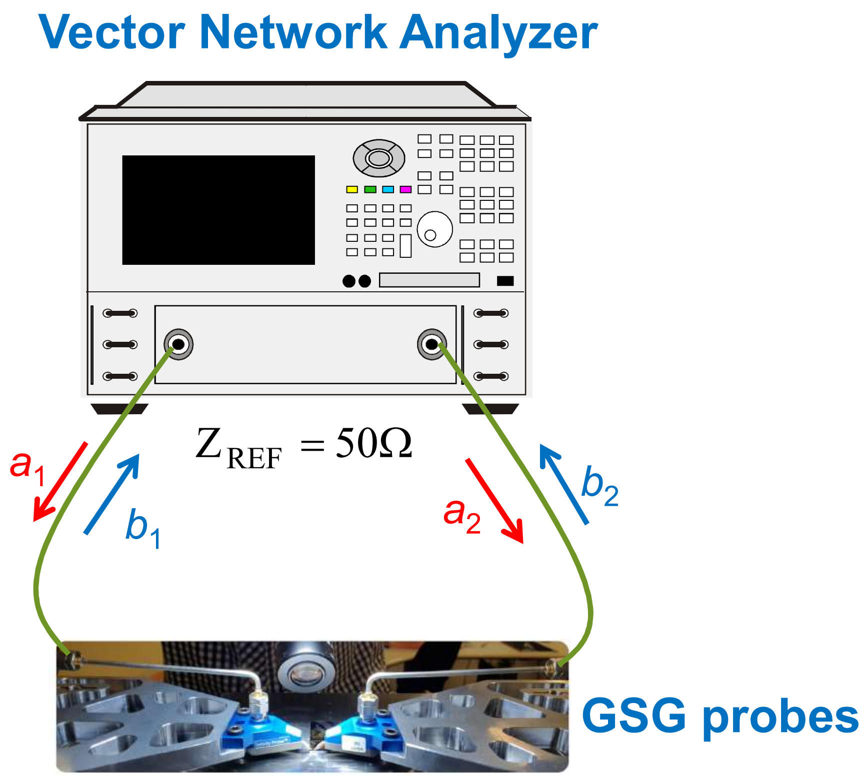
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

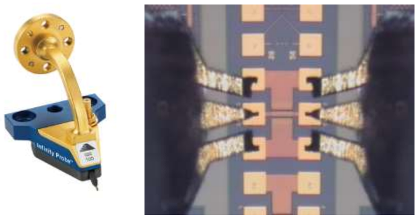
This project will **enable the traceable measurement and characterisation** of integrated circuits and components from radio-frequency to sub-mm frequencies with known measurement uncertainties.

- On-wafer up to 110 GHz
- **University Lille – IEMN** focused on extension to nanoscale dimensions up to 30 GHz (tapered CPW TL vs IEMN set-up)

- Forschungsverbund Berlin e.V. (Germany)
- Fraunhofer-Gesellschaft zur Foerderung der angewandten Forschung e.V. (Germany)
- Friedrich-Alexander-Universität Erlangen - Nürnberg (Germany)
- RF360 Europe GmbH (Germany)
- ROHDE & SCHWARZ GmbH & Co. Kommanditgesellschaft (Germany)
- Technische Universiteit Delft (Netherlands)

On-wafer measurement : TEM guided approach





$$a_i = \frac{\sqrt{\mathrm{Re}(Z_{ref}^i)}}{2|Z_{ref}|}(V_i + Z_{ref}^i I_i)$$

$$b_i = \frac{\sqrt{\mathrm{Re}(Z_{ref}^i)}}{2|Z_{ref}|}(V_i - Z_{ref}^i I_i)$$

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

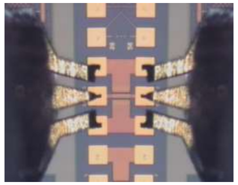
- 1.1 THz
- Contact pads = 30 x 30 μm^2
- Pitch = 25 μm
- Micro-Positioning 1μm /rot. 0.5°
- Optical vizualization

Marks, Roger B., and Dylan F. Williams. "A general waveguide circuit theory." *J. Research of the NIST* 97.5 (1992)

Objective/Challenge

Determine the **calibrated (and guided) *S*-parameters** up to **30 GHz** of CPW micro- and nanodevices with pads contacts smaller than **5 µm^2**

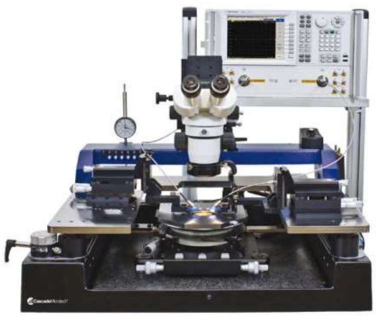
CONVENTIONAL



GSG probe

Contact pad area = 30 x 30 µm^2

Pitch > 25 µm

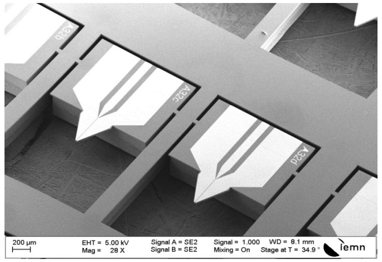


Micropositionner

1µm /rot. 0,5°

Optical visualisation

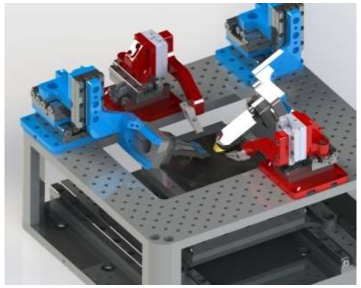
EQPX – ELEMENT 1



GSG Micro-probe

Contact pad area < 5 µm^2

Pitch = 2.5 µm



Robotic nanopositionner

10nm /rot. ~ 1µ°

Scanning electron microscope

10nm

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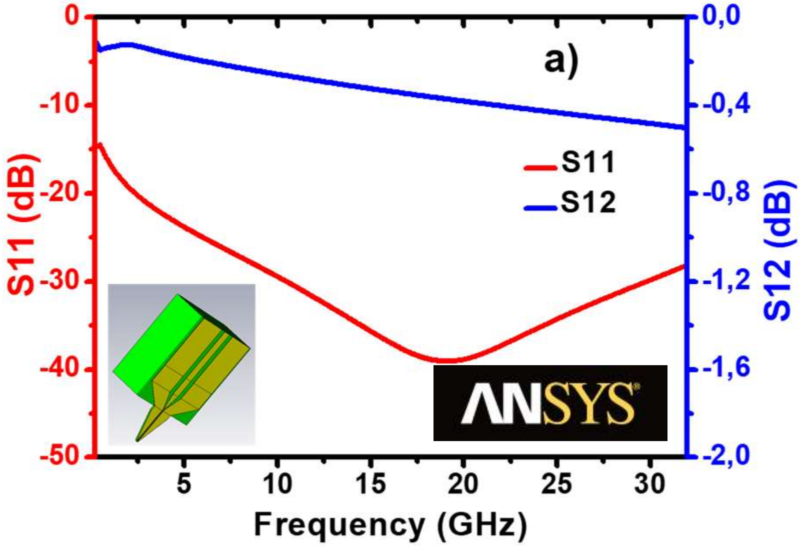
Région Hauts-de-France Nord Pas de Calais - Picardie

ExCELSiOR NANOSCIENCES CHARACTERIZATION CENTER

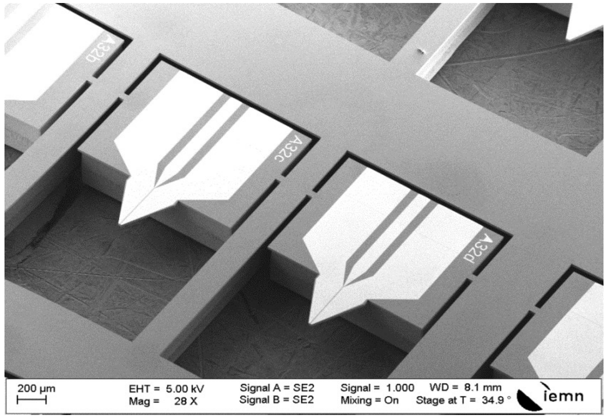
Robotic Microwave On-Wafer probe Station in a Scanning Electron Microscope

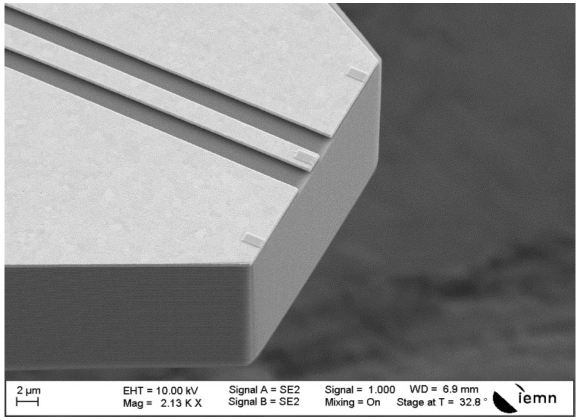
MEMS probe: Design and Fabrication

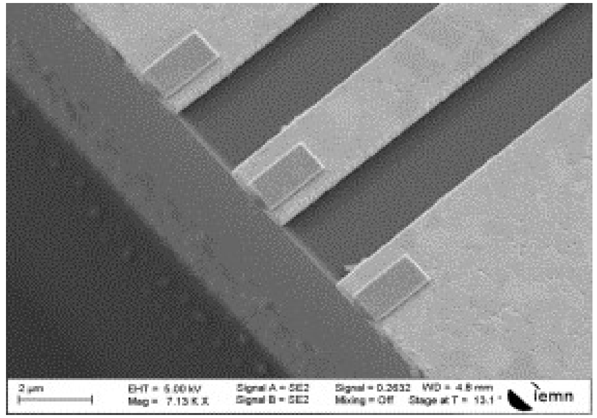
- CPW technology
- Die ~1 x 1 mm²
- 400 µm SOI process
- 500 nm of gold metallization
- Thickness of the cantilever = 20 µm
- Central line width = 2 µm
- Gap width = 2.5 µm
- Characteristic impedance = 50 Ω



1st generation of MEMS probes





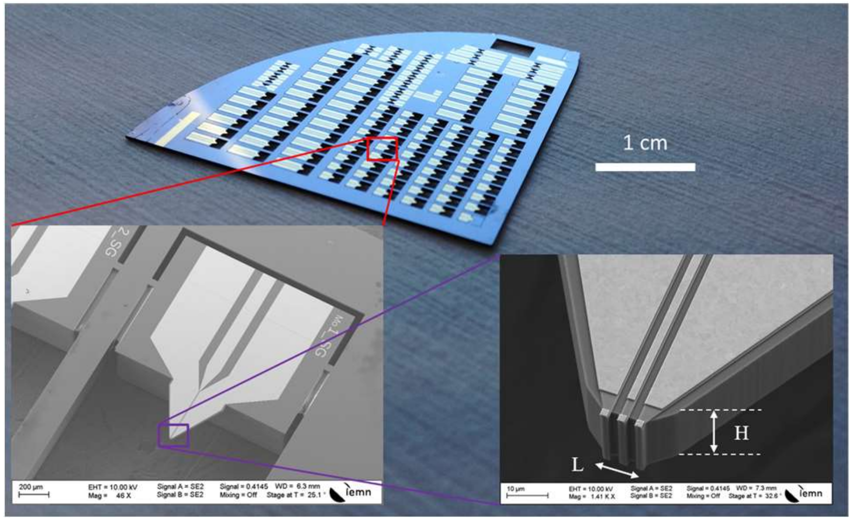


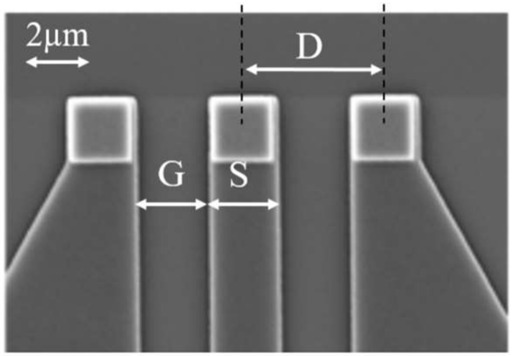
J. Micromech. Microeng. 25 , 7 (2015) 075024

GSG probes & Calibration kit

Miniaturized Probe

- GSG (Ground-Signal-Ground) topology
- MEMS (Microelectromechanical system)
- Substrate (SOI HR, 400µm)
- Different contacting material / size / shape





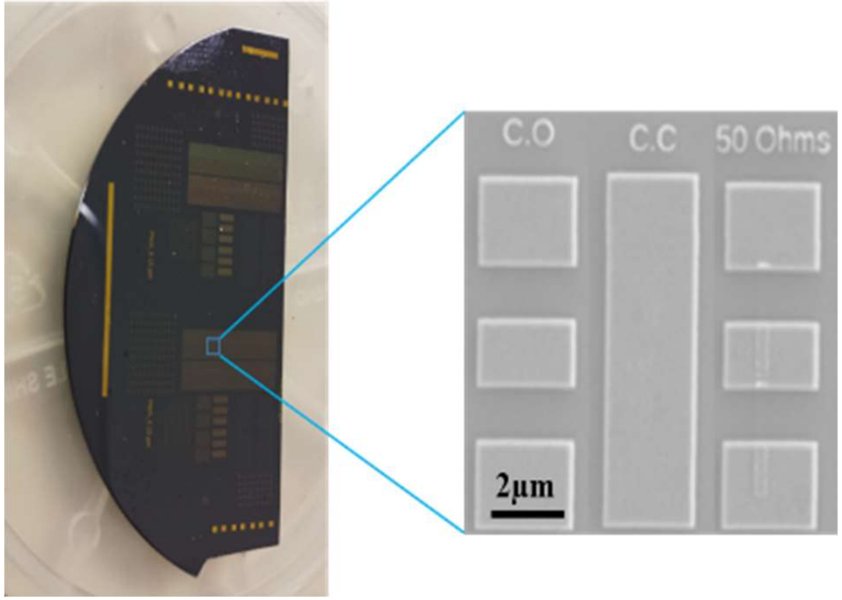
D =4.5µm

G =2.5µm

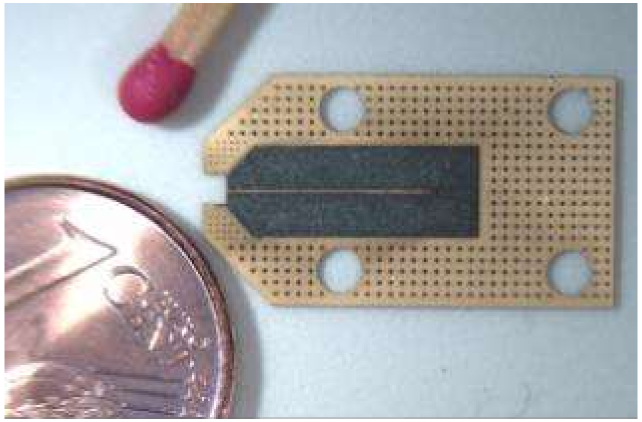
S = 2 µm

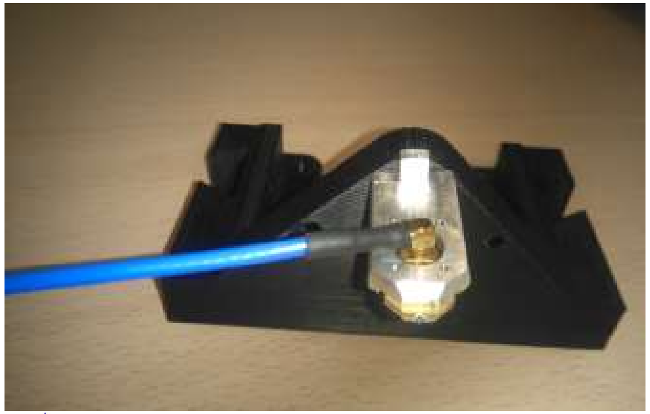
Cal Kit characteristics

- Substrate: GaAs (380µm)
- Metallization: Gold (500 nm)
- Resistive layer: NiCr(20nm)

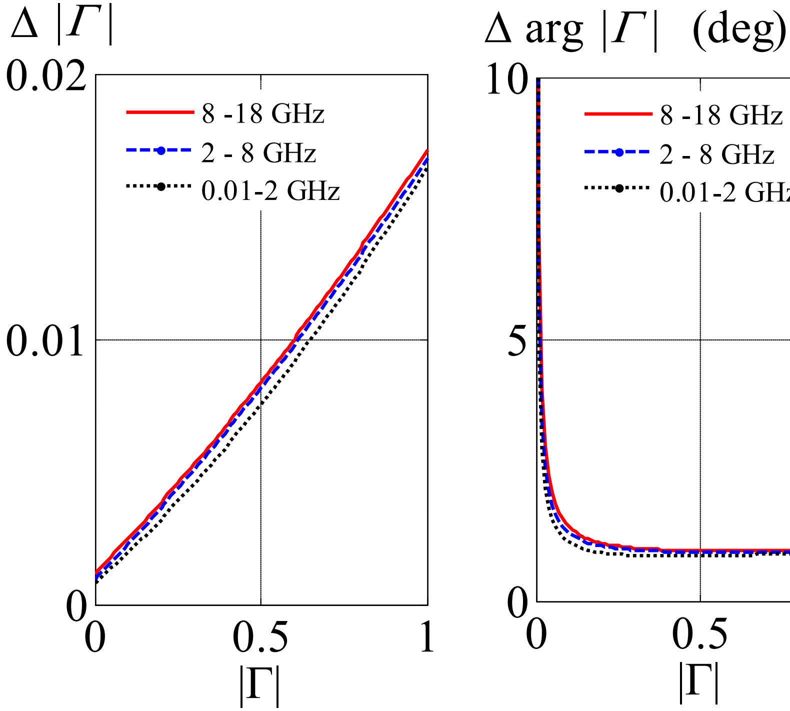


Integration up to 20 GHz





LEAF EquipEX



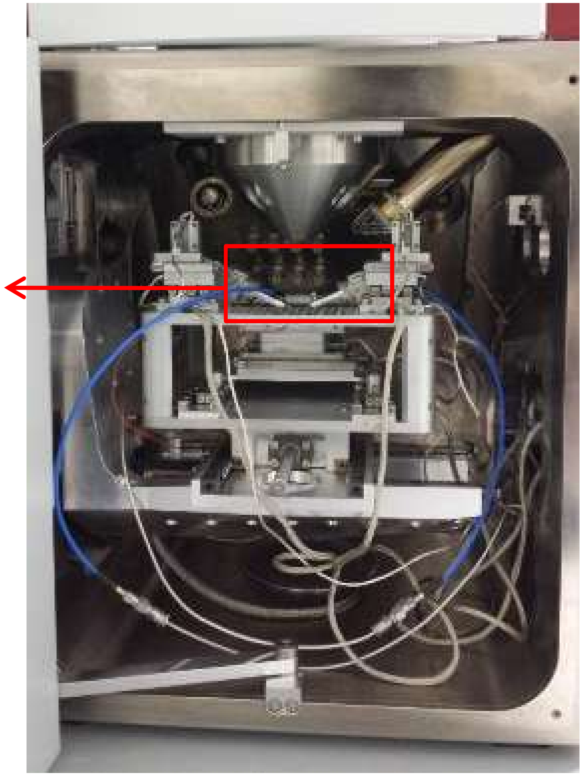
Magnitude and phase-shift measurement uncertainties of the reflection-coefficient Γ as a function of the magnitude of Γ

Set-up vector calibration

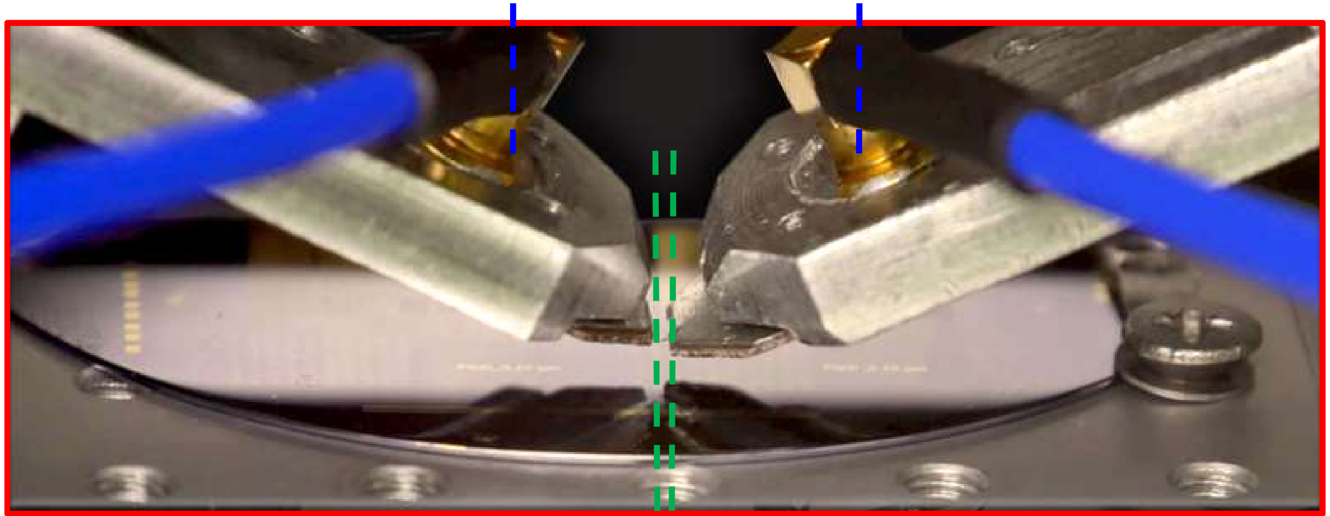
Calibration Procedure

- VNA Keysight™ N5245A PNA-X
- P_{RF} = -10 dBm
- IFBW = 100 Hz

μ-Prober-in-SEM



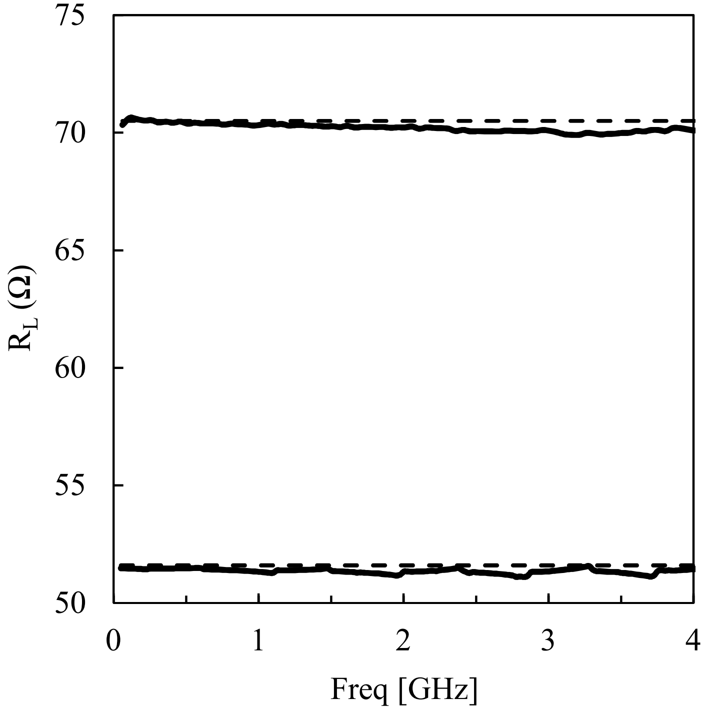
(1) Coaxial ref. plans : One-Port SOL calibration



(2) On-wafer probe tips ref. plans: One-Port SOL calibration

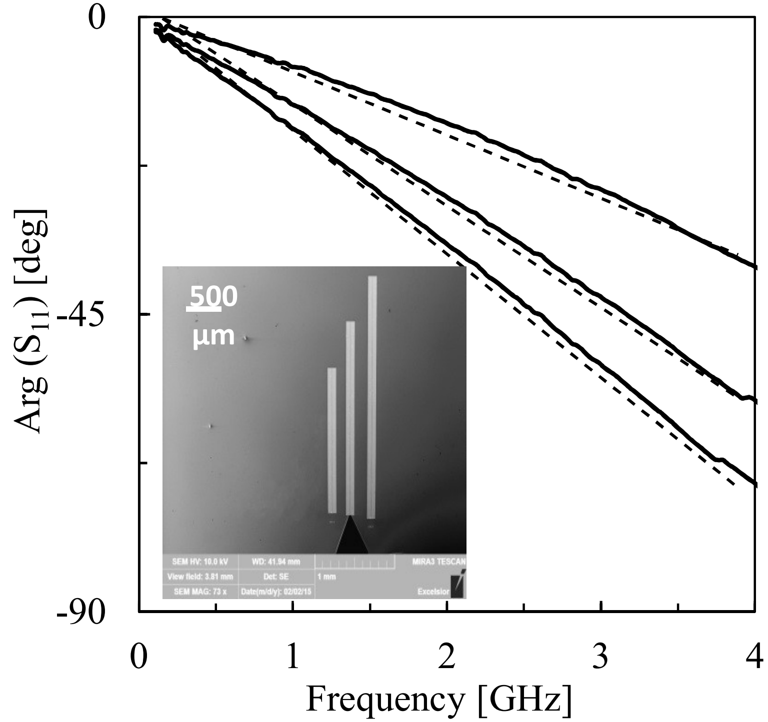
Calibrated Measurements

(1) Resistance



- - R_L (DC) — R_L (RF)

(2) Open-ended CPW TL



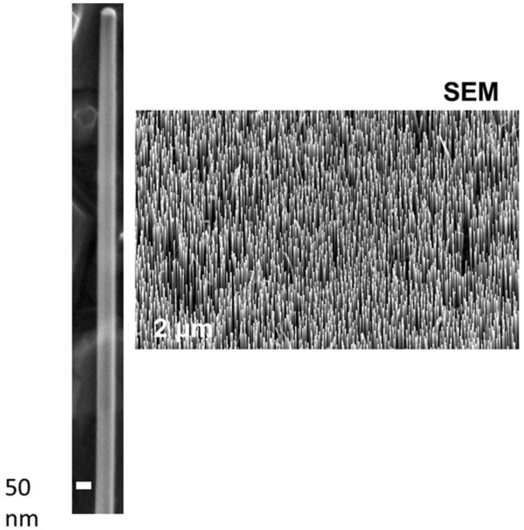
- - Simulated (ADS) — Measured
(L = 1.5 mm, 2 mm, 2.5 mm)

Accurate on-wafer characterization of complex impedances

Application to 1D InAs nanodevice measurement

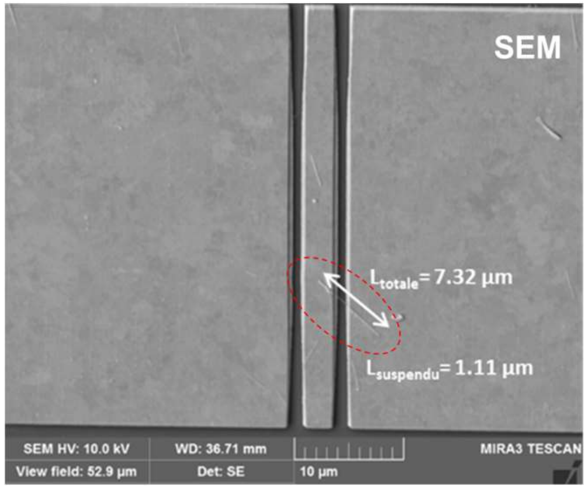
Nanofabrication

- Vertical configuration
- Vapour-Solid-Liquid
- InP substrate
- gold particles as catalyst agent
- diameter ~70 nm

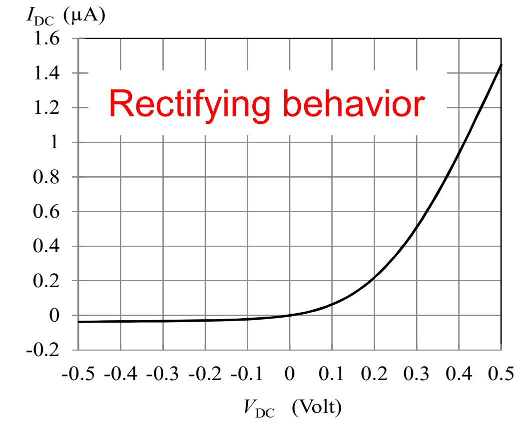


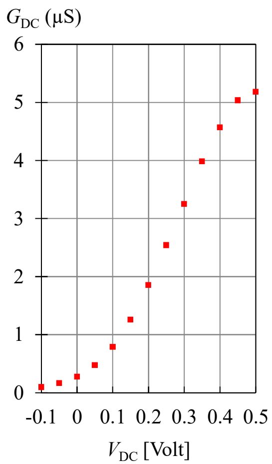
CPW integration

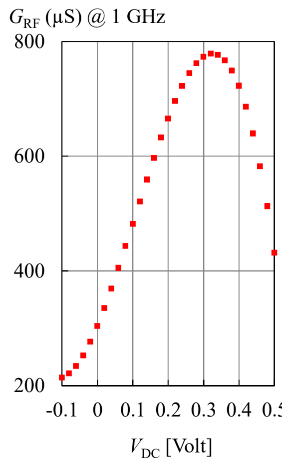
- CPW gap = 1.8 µm
- drop of NW/isopropanol sol.
- 500 nm **Au** layer deposition (electrical contacts)
- total length ≈ 7µm
- Suspended length ≈ 1µm



RF TEST







Daffe, K., Marzouk, J., El Fellahi, A., Xu, T., Boyaval, C., Eliet, S., Grandidier, B., Arscott, S., Dambrine, G. and Haddadi, K., 2017, October. Nano-probing station incorporating MEMS probes for 1D device RF on-wafer characterization. In *2017 47th European Microwave Conference (EuMC)* (pp. 831-834). IEEE.

A guideline for 1D material RF meas.

K. Daffe, Y. Coffinier, I. Roch-Jeune, C. Boyaval, G. Dambrine, K. Haddadi, Univ. Lille,
F. von Kleist-Retzow, C. Haenssler, S. Fatikow, Carl von Ossietzky Universität Oldenburg, Oldenburg, Germany
H. Votsi, C. Li, PH Aaen, Advanced Technology Institute, University of Surrey, Guildford, United Kingdom
H. Votsi, N. Ridler, National Physical Laboratory, Teddington, United Kingdom
V. Mascolo, F. Mubarak, VSL, Van Swinden Laboratorium, Delft, The Netherlands
A. Buchter, J. Hoffmann, Federal Institute of Metrology METAS. Köniz, Switzerland
U. Arz, Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany

1 – Calibration and test tapered CPW structures design, fab & RF test

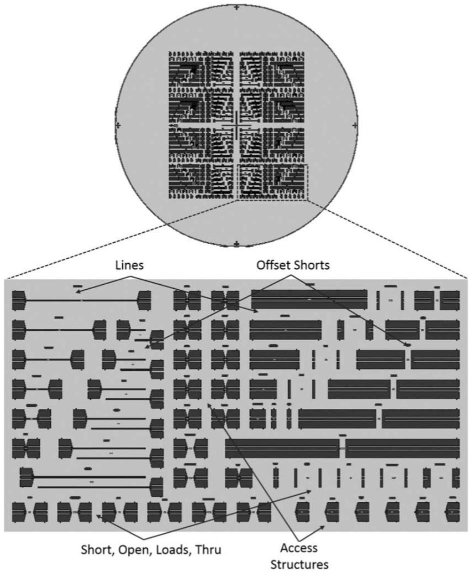


Fig. 2. Layout of the fabricated 3 inch wafer including all the access structures and calibration standards.

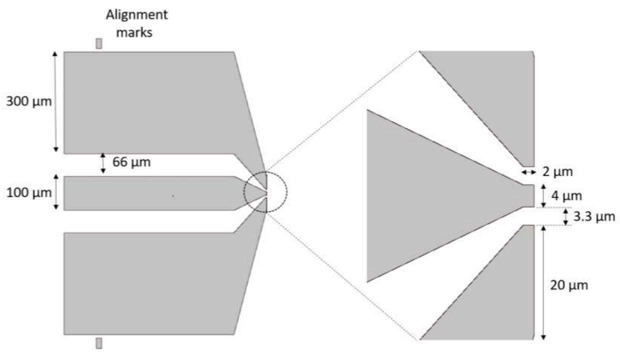


Fig. 1. Open-circuit calibration standard included in the fabricated wafer. The dimensions shown were selected to achieve a 50-Ω characteristic impedance across the entire structure.

Parameters	*4 µm gap Meas. [nom]*
Wi(µm)	102 [100]
W(µm)	299 [300]
D(µm)	65 [66]
H(µm)	1.7 [1.8]
Ws(µm)	2.4 [2.3]
Wr(µm)	3.9 [4]
Lr(nm)	110 [100]

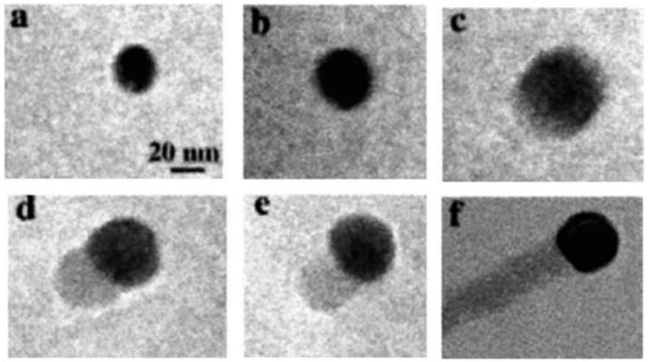
A guideline for 1D material RF meas.

2 – Silicon nanowires fabrication

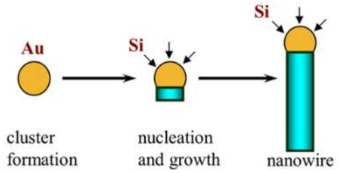
Silicon nanowires (SiNWs) used in this work were prepared using the vapor-liquid-solid (VLS) mechanism.

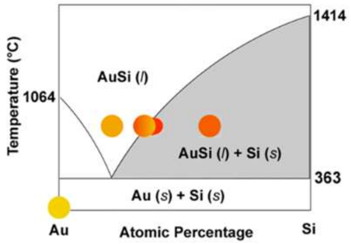
The fundamental process is based on metal-catalyst-directed chemical vapor deposition of silicon. First, a thin film of gold (4 nm thick) was evaporated on the clean Si substrate. Gold nanoparticles with a wide size distribution were obtained as a result of metal dewetting on the surface.

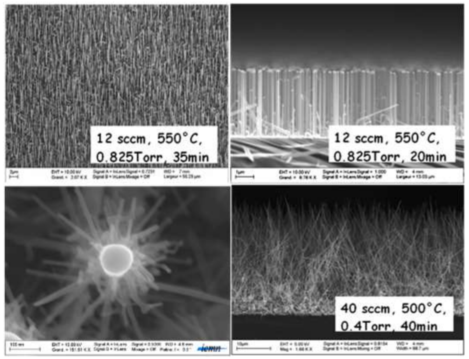
Exposure of the gold-coated surface to silane gas at a pressure of 0.4 T with 40 sccm at 500 °C during 20 min in a dedicated furnace, led to SiNWs growth. The nanowires are terminated by gold nanoparticles according to the VLS mechanism.

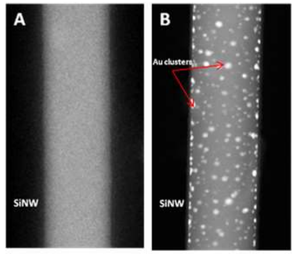


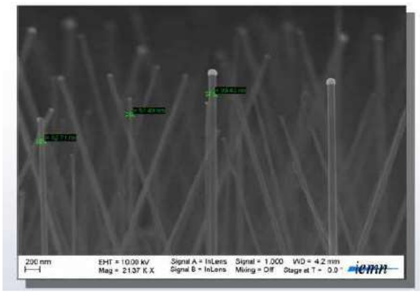
a- Catalyseur métallique
b- Eutectique Au-Si
c-Nucleation à l'interface liquide/solide – Formation du crystal de Si
d et e Elongation du crystal de Si
f- Nanofil de Si





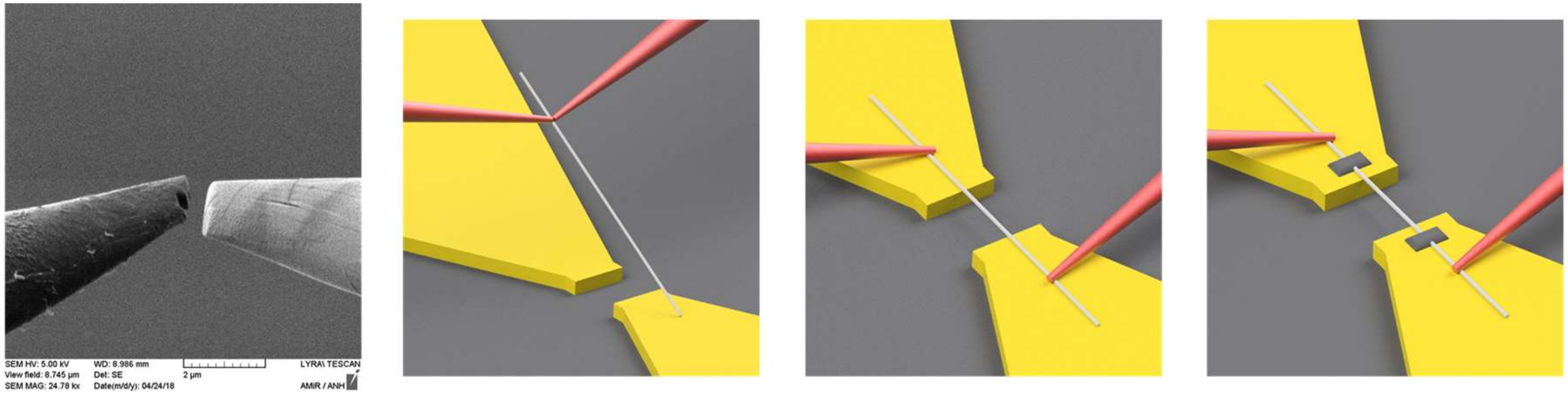






A guideline for 1D material RF meas.

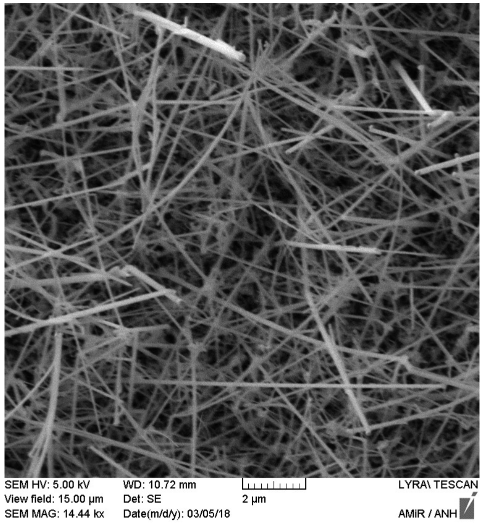
3 – Handling, nanomanipulation and soldering under scanning electron microscopy

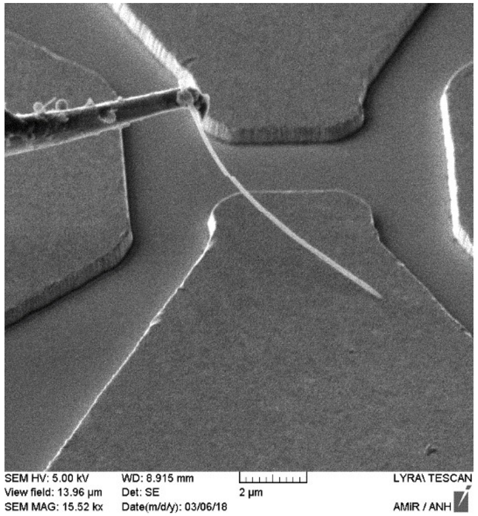


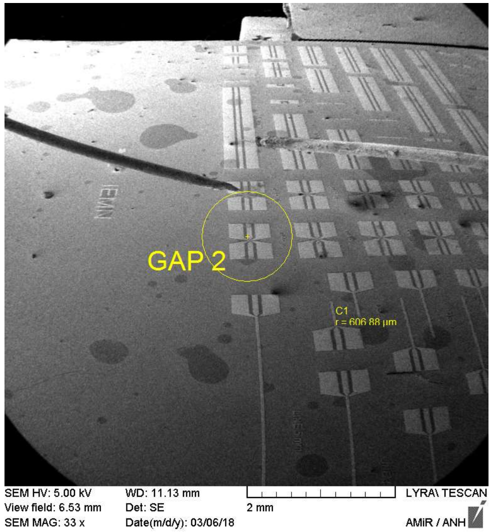
I)	II)	III)	IV)
• Prepare the tips with FIB milling • One tip is customized with an adhesion pocket in the size of the nanowire (NW)	• NW is picked up and brought (by automated movement of 100µm/s to minimize vibrations) to the desired CPW gap • One side of the NW is connected to gold pad for minimize electrostatic charging • Afterwards tip without adhesion pocket is disconnected from NW	• NW is aligned to the gap in the optimal position • Each side of NW is fixated with one tip to minimize the risk of losing the NW due to outgassing of the gas injection system (GIS) -> force on NW	• Electron beam induced deposition (EBID) is used to deposit Pt pillows on top of each side of the NW to fix it to the gold • Tips are removed

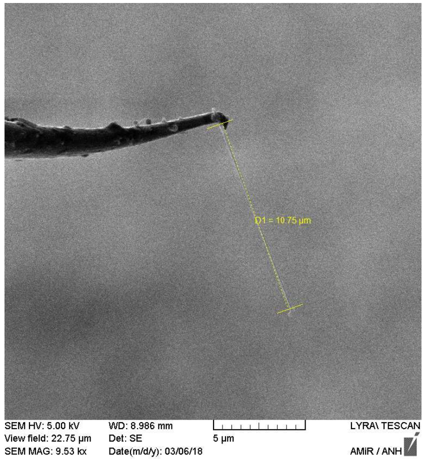
A guideline for 1D material RF meas.

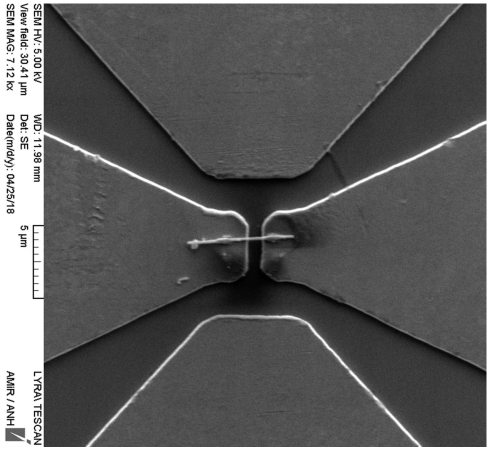
3 – Handling, nanomanipulation and soldering under scanning electron microscopy

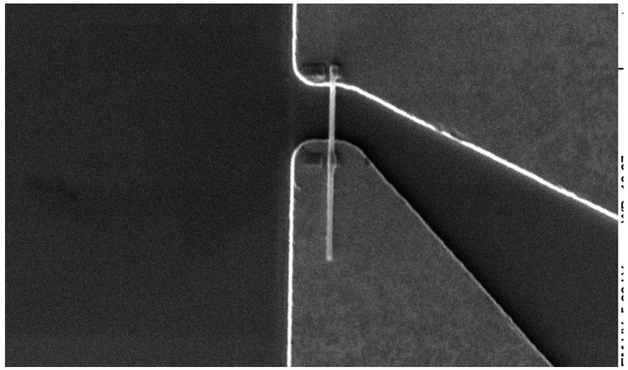








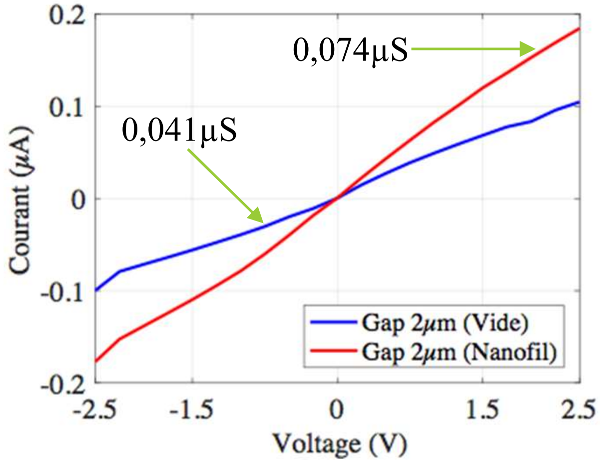


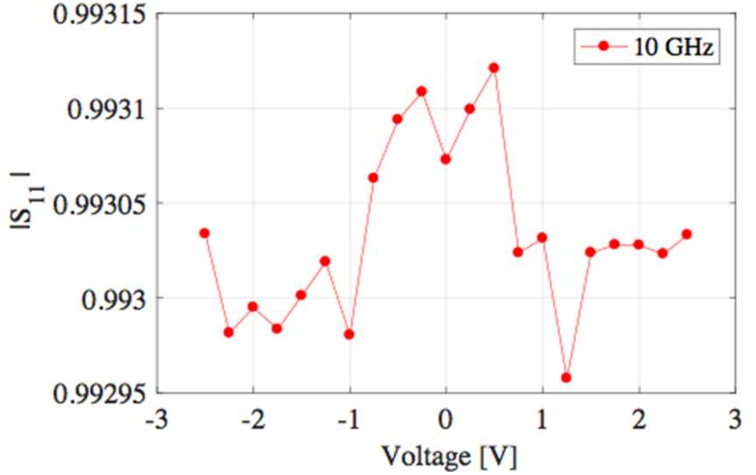


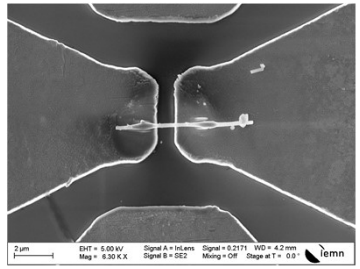
A guideline for 1D material RF meas.

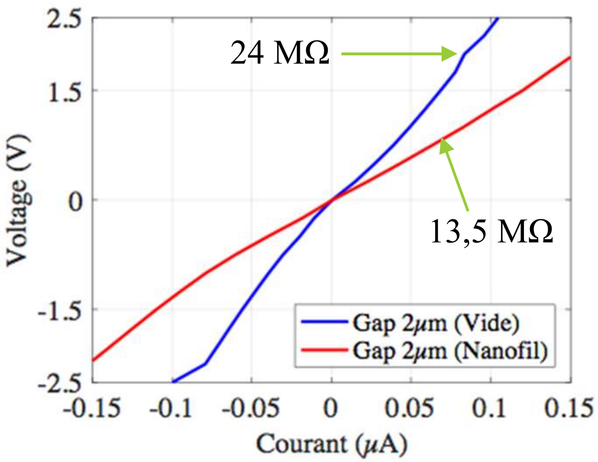
3 – DC measurements (empty & loaded CPW structures)

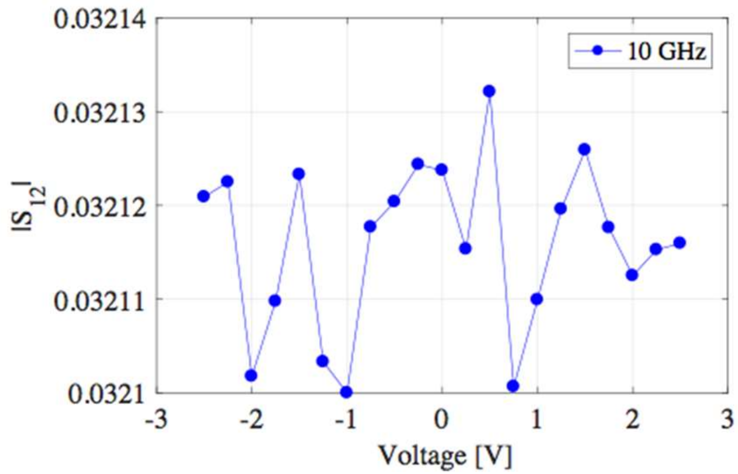
Raw S-paramaters = f(Vg)







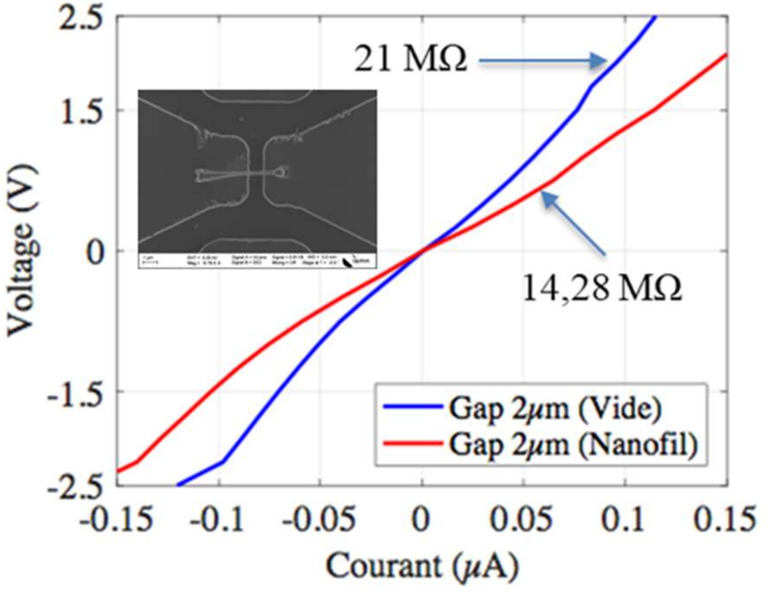


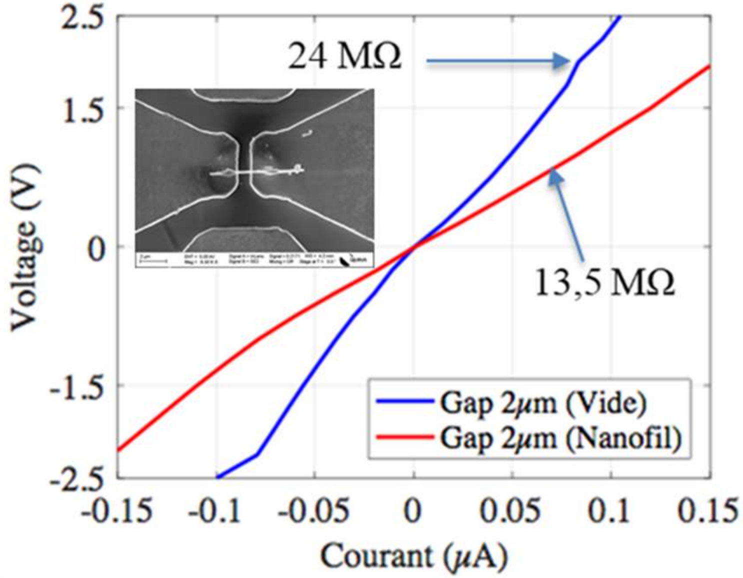


Microwave response not sensitive to DC bias

A guideline for 1D material RF meas.

3 – DC measurements (empty & loaded CPW structures)

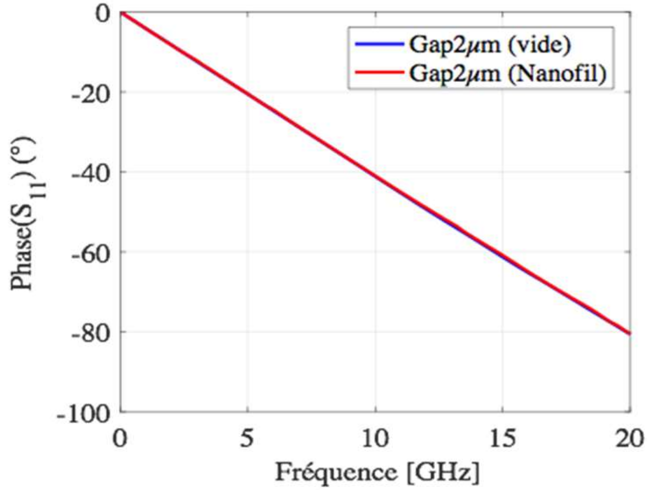


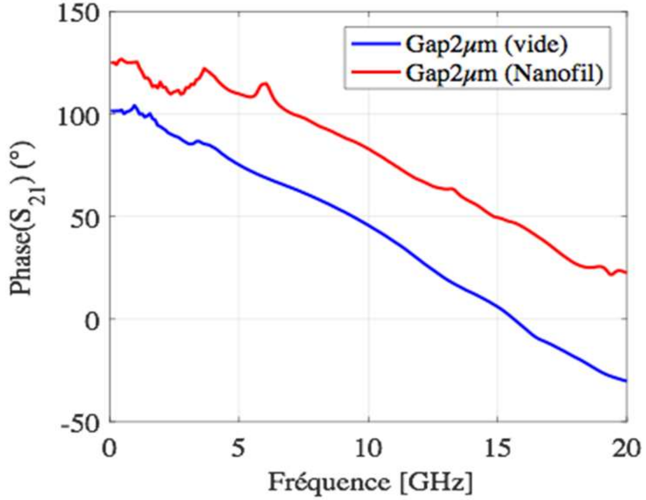


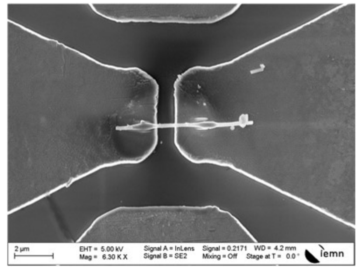
Process reproducibility : 2 test structures loaded with NWs

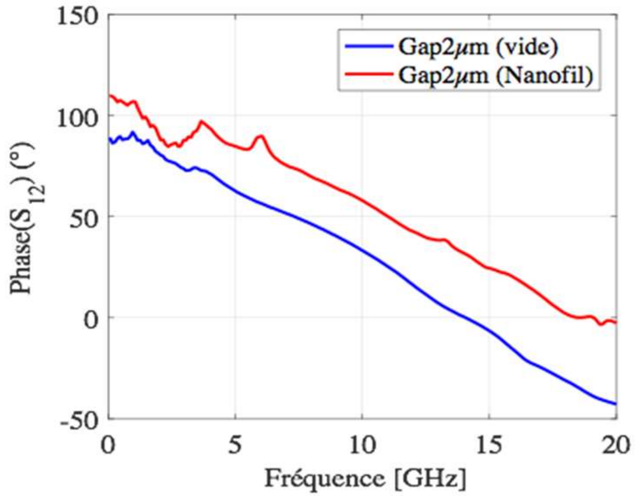
A guideline for 1D material RF meas.

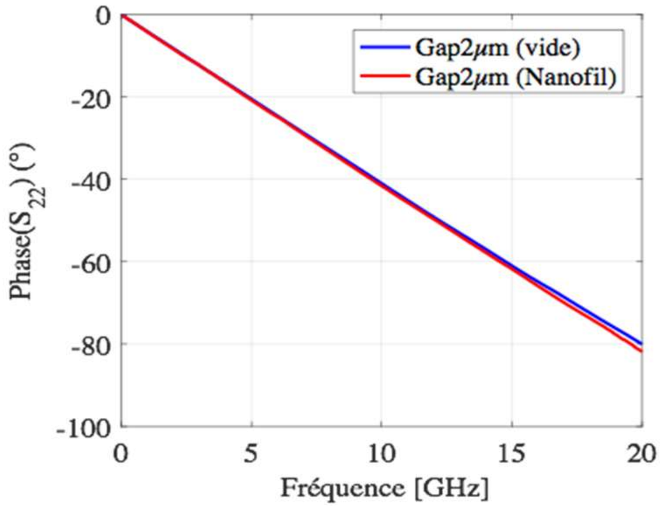
3 – RF measurements (empty & loaded CPW structures)











THANK YOU

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European Union
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The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

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Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

TEMMT-Workshop:
WP 3 - Calibration of RF power at D-Band

Gia Ngoc Phung, Karsten Kuhlmann, Jürgen Rühaak, AG 2.22

Physikalisch-Technische Bundesanstalt,
Braunschweig, Germany

Outline

- Motivation: RF power
- Measurement principles
  - Direct comparison
  - Microcalorimeter
- Measurement Results at D-Band
- Summary and Conclusion

Motivation

Motivation

RF derived quantities

- Scattering parameters
- Calibration of power sensors
- Antenna gain and factor
- Feld strength
- Power density
- Specific absorption rate
- Channel characterization for Broadband communication up to the THz-range
- On-wafer-measurements
- Dielectric materials properties

→

RF base quantities

- RF power
- RF impedance
- RF attenuation
- RF voltage

→

Traceability to SI

- DC quantities
- Length
- Frequency

RF Power Measurement

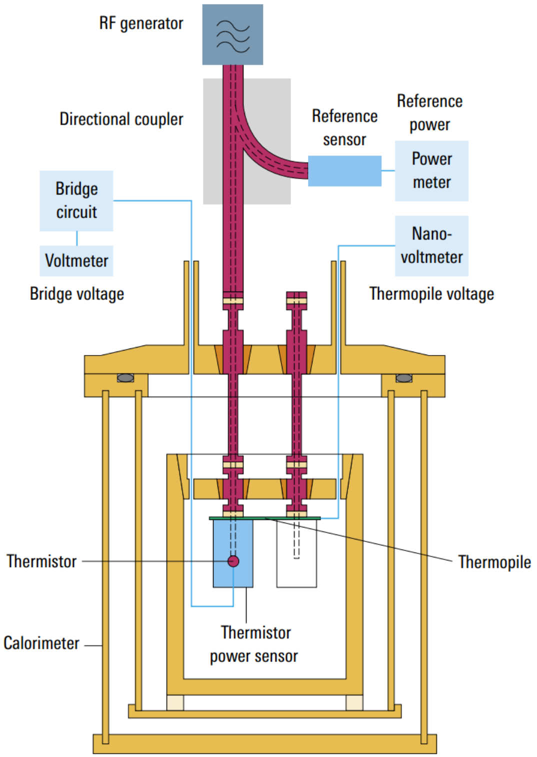
- **Usually two requirements:**
- Power sensor (detector)
- Power meter (base unit)

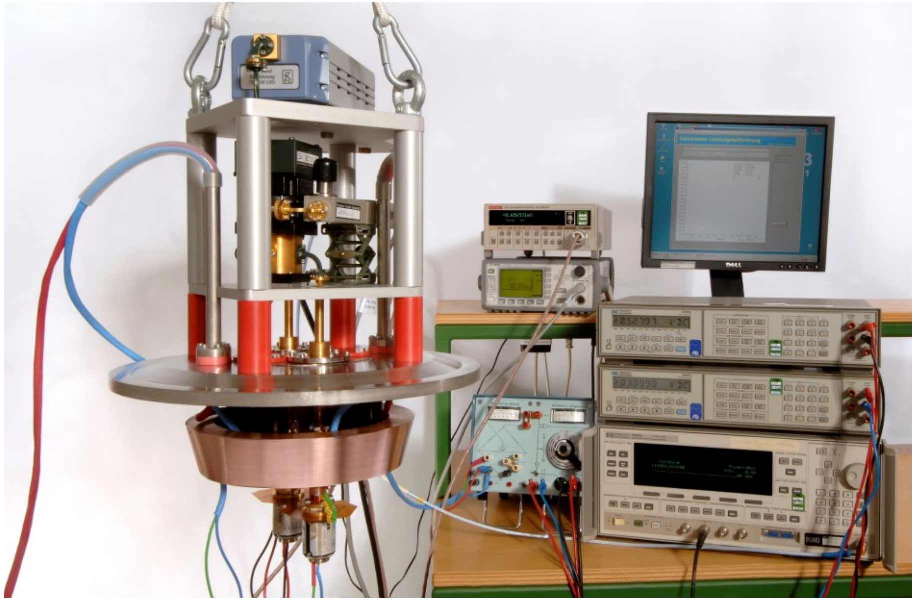
RF power sensor (detector)

	Diode	Thermoelectric	Thermistor
Sensitivity	High	Medium	Low
Speed	High	Medium	Low
Linearity	Low	High	High
Dynamic range	High	Medium	Low
Traceability	Not suitable	Medium	Good

Calibration Method

Microcalorimeter (I)

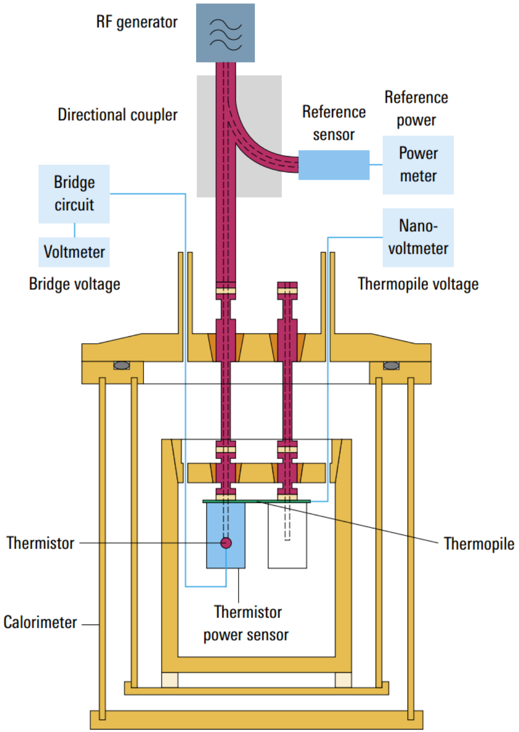


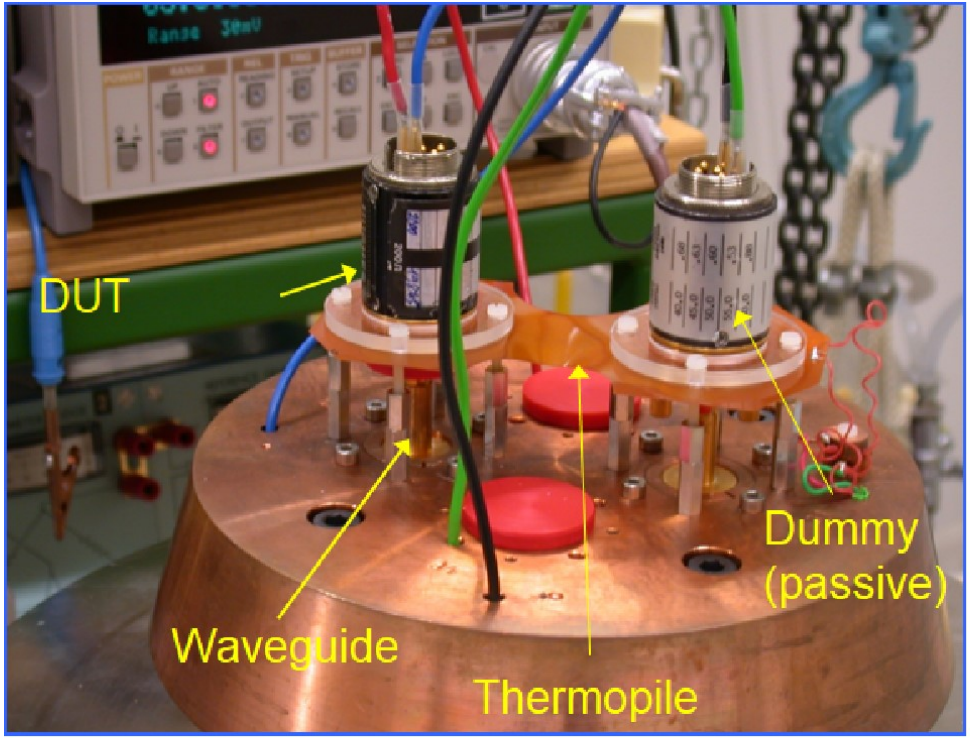


Example R900

- Symmetrical set-up
- Rect. waveguide or coaxial
- High thermal stability
- Large thermal time constant
- Nominal power: 1 to 10 mW

Microcalorimeter (II)





Measurement Quantities

Effective efficiency

$$\eta_{eff} = \frac{P_{ind}}{P_{RF,abs}} = \frac{P_{DC,sub}}{P_{RF,abs}}$$

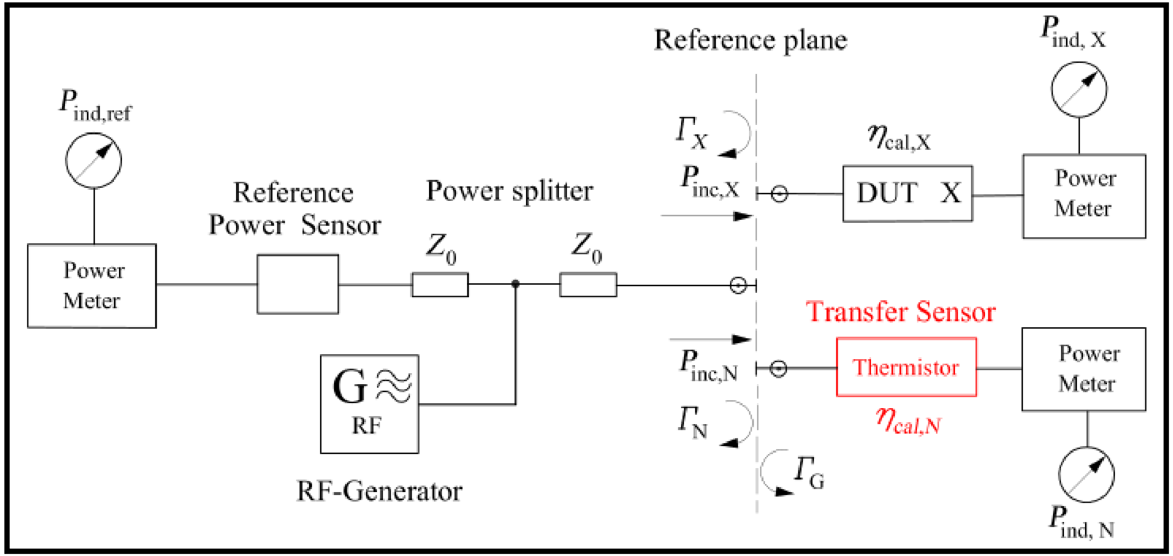
Thermistor

Calibration factor

$$\eta_{cal} = \frac{P_{ind}}{P_{inc}} = (1 - |\Gamma|^2)\,\eta_{eff}$$

Direct Comparison Method

Sensor calibration by direct comparison method



$$\eta_{cal,X} = \eta_{cal,N} \cdot \frac{P_{ind,X}}{P_{ind,ref,X}} \cdot \frac{P_{ind,ref,N}}{P_{ind,N}} \cdot \frac{\left|1-\Gamma_G \Gamma_X\right|^2}{\left|1-\Gamma_G \Gamma_N\right|^2}$$

Needed:
Calibrated transfer sensor with low uncertainties.
Traceable to SI

Uncertainty in the Frequency Bands

Frequency ranges	Microcalorimeter	Direct comparison
10 MHz - 8 GHz	0.002 (coaxial)	0.003 - 0.004 (coaxial)
8 GHz - 18 GHz	0.003 (coaxial)	0.005 - 0.007 (coaxial)
18 GHz - 26.5 GHz	0.002 (waveguide)	0.013 (coaxial) 0.007 (waveguide)
26.5 GHz - 40 GHz	0.0032 (waveguide)	0.018 – 0.020 (coaxial) 0.009 (waveguide)
33 GHz - 50 GHz	0.008 - 0.016 (waveguide)	0.015 - 0.018 (coaxial) 0.012 (waveguide)
50 GHz - 75 GHz	0.012 - 0.019 (waveguide)	0.016 (waveguide)
75 GHz - 110 GHz	0.016 - 0.026 (waveguide)	0.020 (waveguide)

Measurement time:
Microcalorimeter: appr. 18 h per frequency point
Direct comparison: appr. 2 h per frequency point

Longer measurement time but better uncertainty

Measurement Results at D-Band

Current Status of Power Sensors

- Current Status :
  - Use of thermistors for calibration in general
  - Commercial thermistor sensors (Hewlett Packard, Hughes, Millitech) from the 1980s:
    - poor input match
    - limited bandwidth
    - leakage
    - scarce
  - Development of novel power transfer started at Rohde & Schwarz (R&S) supported by PTB around 2010

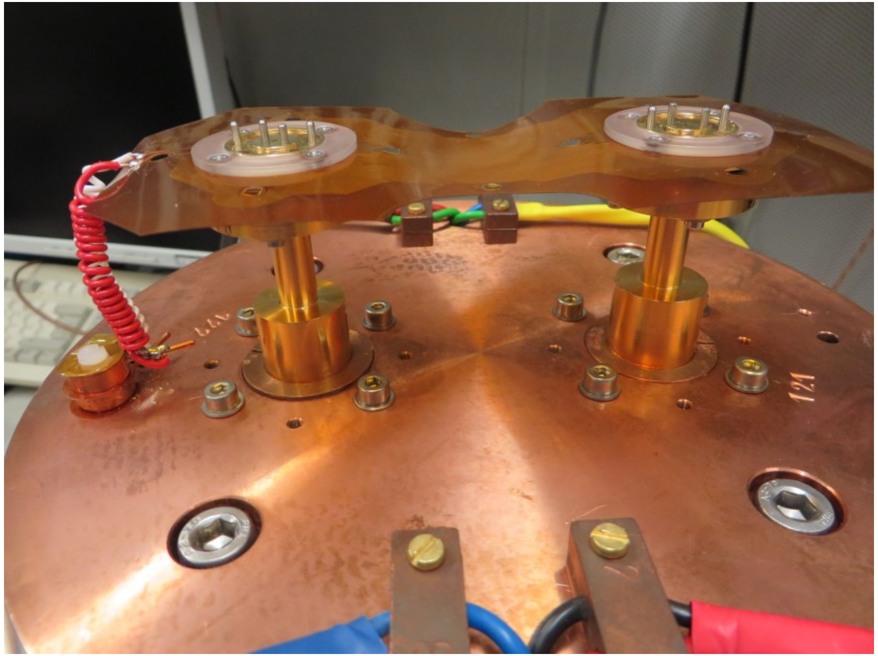
Generalized Efficiency

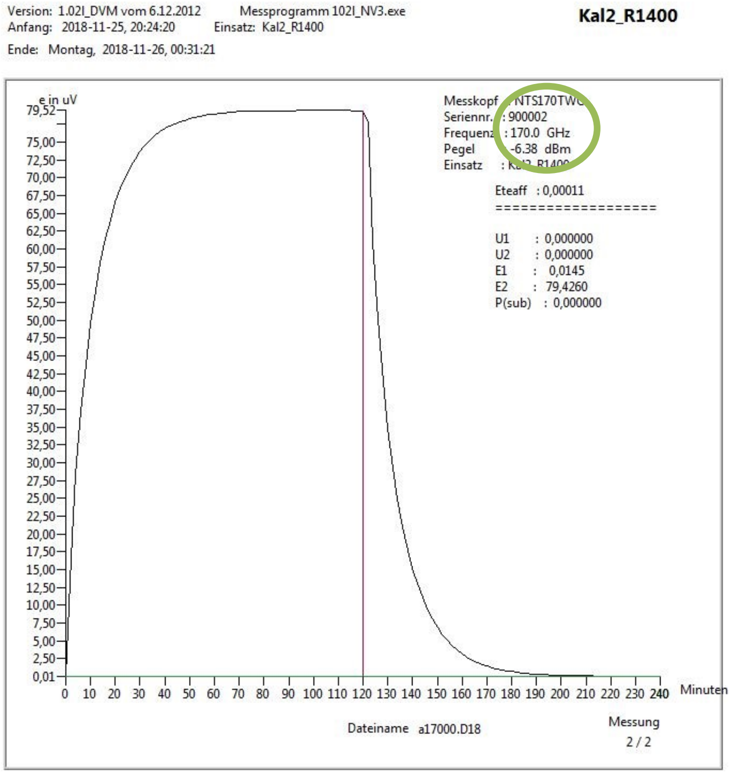
- Due to lack of thermistor sensors at D-Band
- →Development of a sensor is required
- →1st prototype of thermoelectric D-band power transfer standard designed, manufactured and characterized

- Characterization of thermoelectric power sensors
- **→Introduction of generalized efficiency**

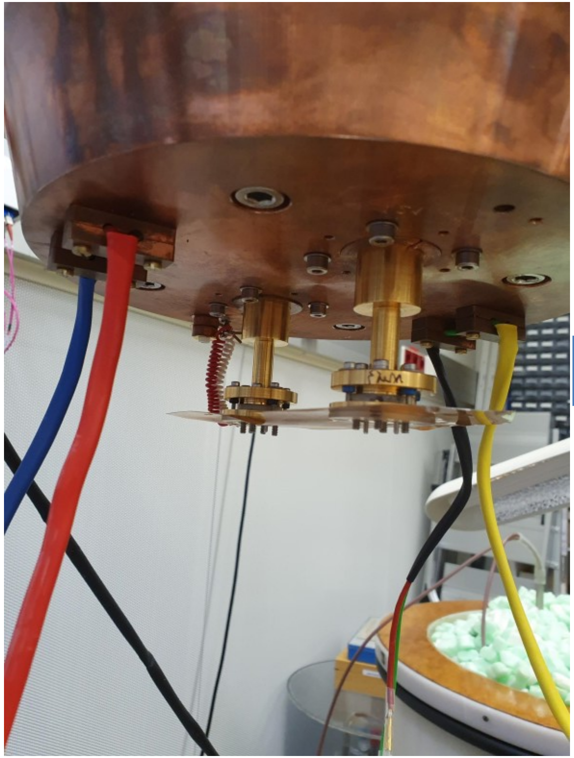
R1400 Waveguide Calorimeter

- R1400 waveguide calorimeter

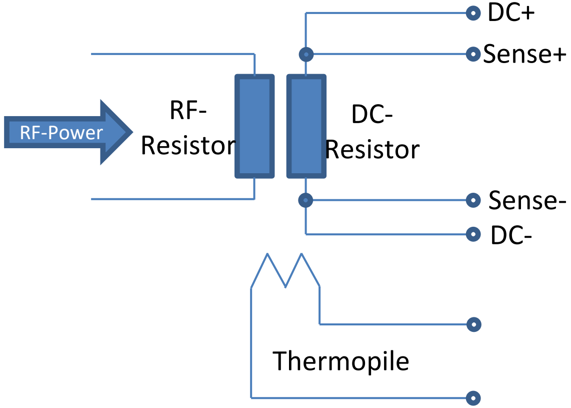




R&S Thermoelectric Power Sensors

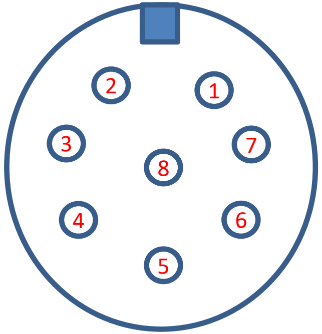


Connection of the R&S Sensor



Signal	Pin	Cable	Connector
DC+	7	Yellow	Yellow
Sense+	4	Purple	Yellow
Sense-	5	Purple	Yellow
DC-	6	Yellow	Yellow
	2	Red	Red
	3	Black	Black

View to the Jack
of the Sensor



Generalized Sensor Efficiency (I)

- Generalized Sensor Efficiency :
  - Figure of merit used to characterize the RF or thermal performance of thermoelectric power sensors
  - Based on four steps
    - Linearity Measurement of Thermopile
    - Multiple Offset Short Measurements
    - Averaging P_{avg} from the Short Measurements
    - **Calculation of Generalized Sensor Efficiency**

Linearity Measurement of Thermopile

Multiple Offset Short Measurements

Averaging Pavg from the Short Measurements

Generalized Sensor Efficiency

Generalized Sensor Efficiency (II)

- **Linearity Measurement of Thermopile**
  - Measurement of DC Voltage
  - Measurement of DC thermal voltage
  - Measurement of DC resistance

$$V_{DC} = v_0 + v_2 - v_1 \quad (1)$$

$$e_{DC} = e_0 + e_2 - e_1 \quad (2)$$

$$P_{dc} = \frac{V_{dc}^2}{r_{dc}} \quad (3)$$

Heating coefficient

$$k_{dum} = \frac{P_{dc}}{e_{dc}} \quad (4)$$

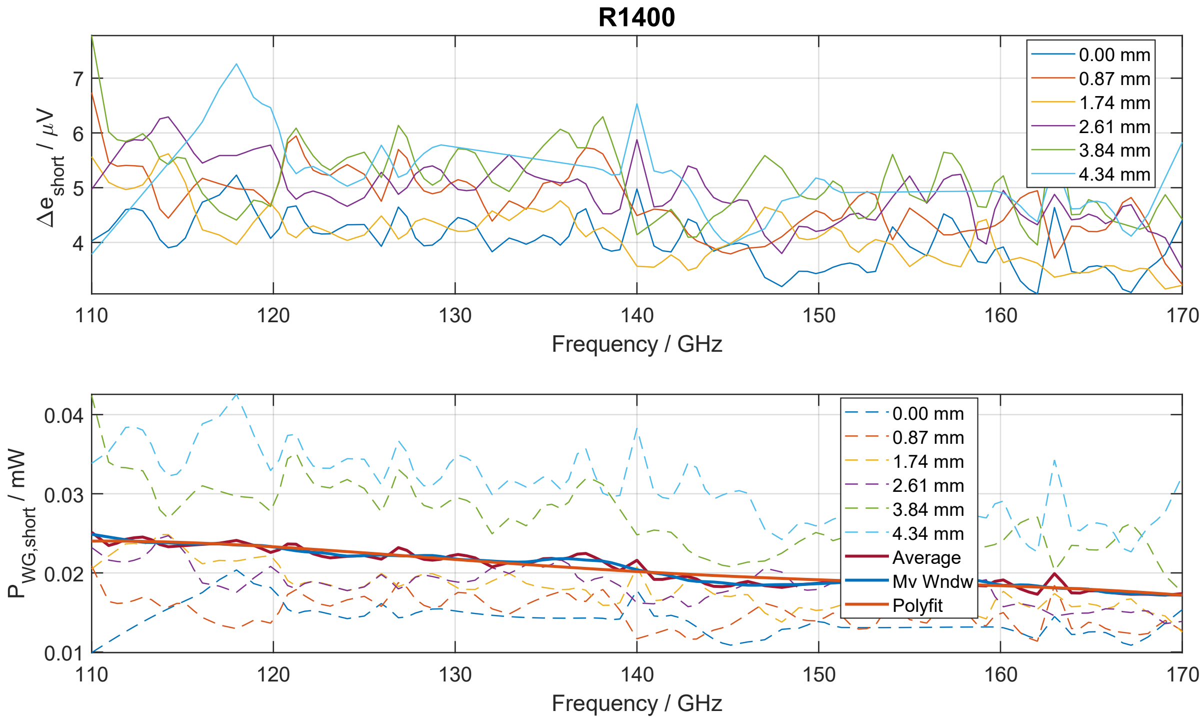
Linearity Measurement of Thermopile

Multiple Offset Short Measurements

Averaging Pavg from the Short Measurements

Generalized Sensor Efficiency

Multiple Offset Short Measurements (I)



Linearity Measurement of Thermopile

Multiple Offset Short Measurements

Averaging Pavg from the Short Measurements

Generalized Sensor Efficiency

Principle of Generalized Sensor Efficiency (I)

- The generalized efficiency

$$\eta_{gen}(f) := \left. \frac{P_{dc}}{P_{RF,abs}(f)} \right|_{V_{th,1}=V_{th,2}}$$

$$p_{cor} = \frac{Q \cdot (1-\Gamma^2)}{1 - \frac{Q \cdot (1+\Gamma^2) \cdot k_2 \cdot V_{th1}}{m \cdot e_1}};$$

$$Q = \frac{P_{AVWG}}{2 \cdot P_{dc}};$$

$$\eta_{gen}(f) = \left(1 + p_{cor} \frac{1+|\Gamma|^2}{1-|\Gamma|^2}\right) \cdot \frac{k_2}{m} \cdot \frac{V_{th,1}}{e_1}.$$

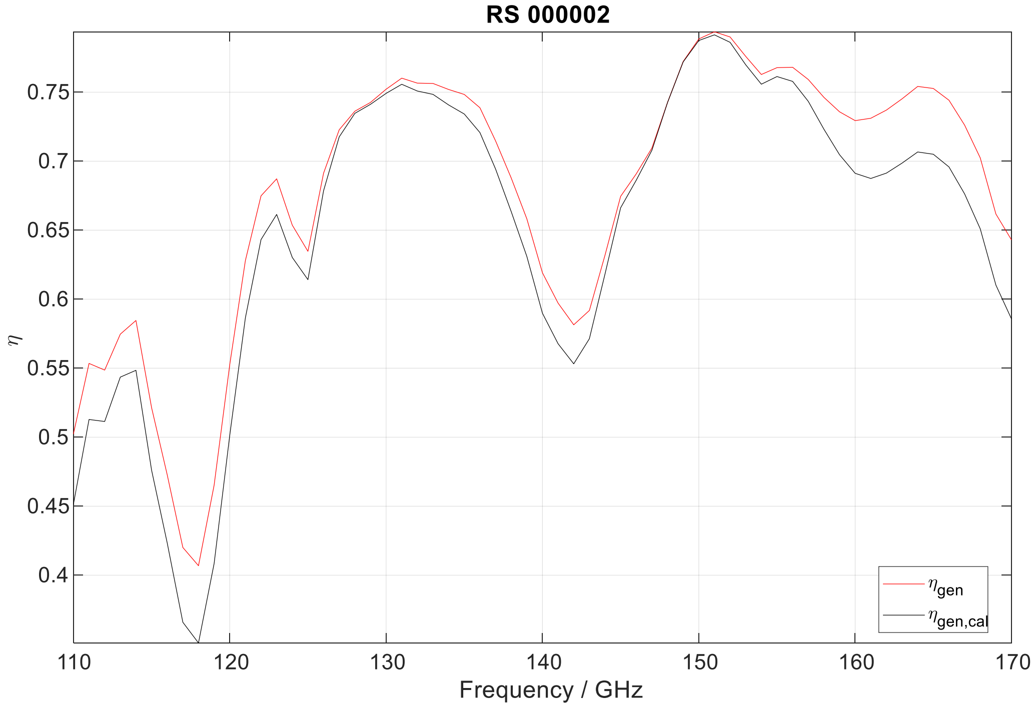
Linearity Measurement of Thermopile

Multiple Offset Short Measurements

Averaging Pavg from the Short Measurements

Generalized Sensor Efficiency

Principle of Generalized Sensor Efficiency (II)



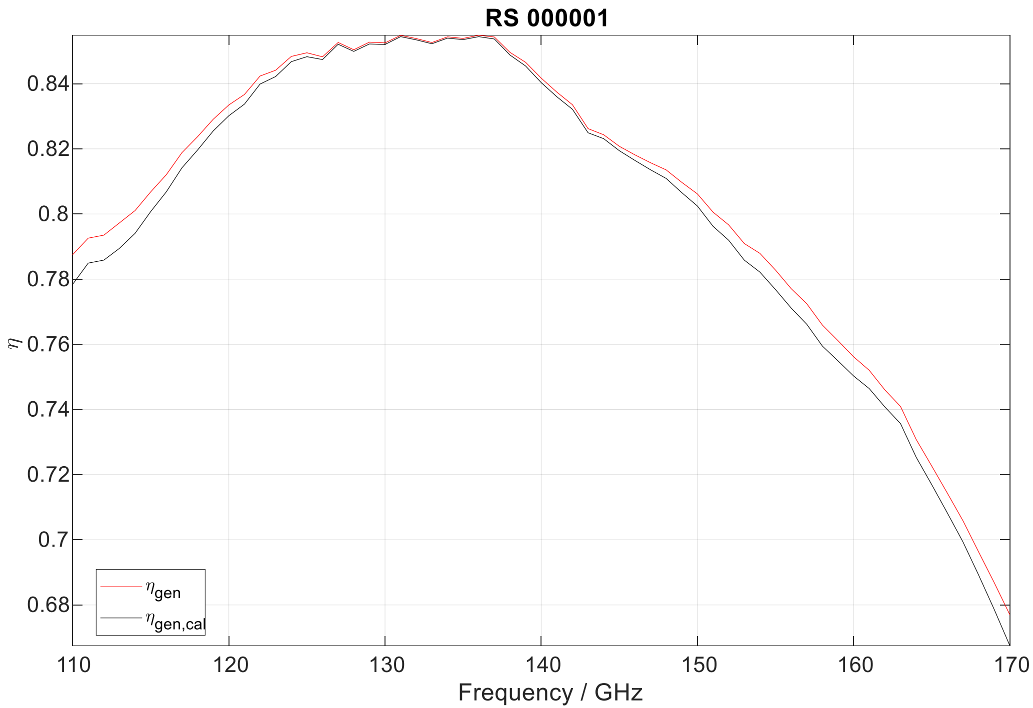
Linearity Measurement of Thermopile

Multiple Offset Short Measurements

Averaging Pavg from the Short Measurements

Generalized Sensor Efficiency

Principle of Generalized Sensor Efficiency (II)



Linearity Measurement of Thermopile

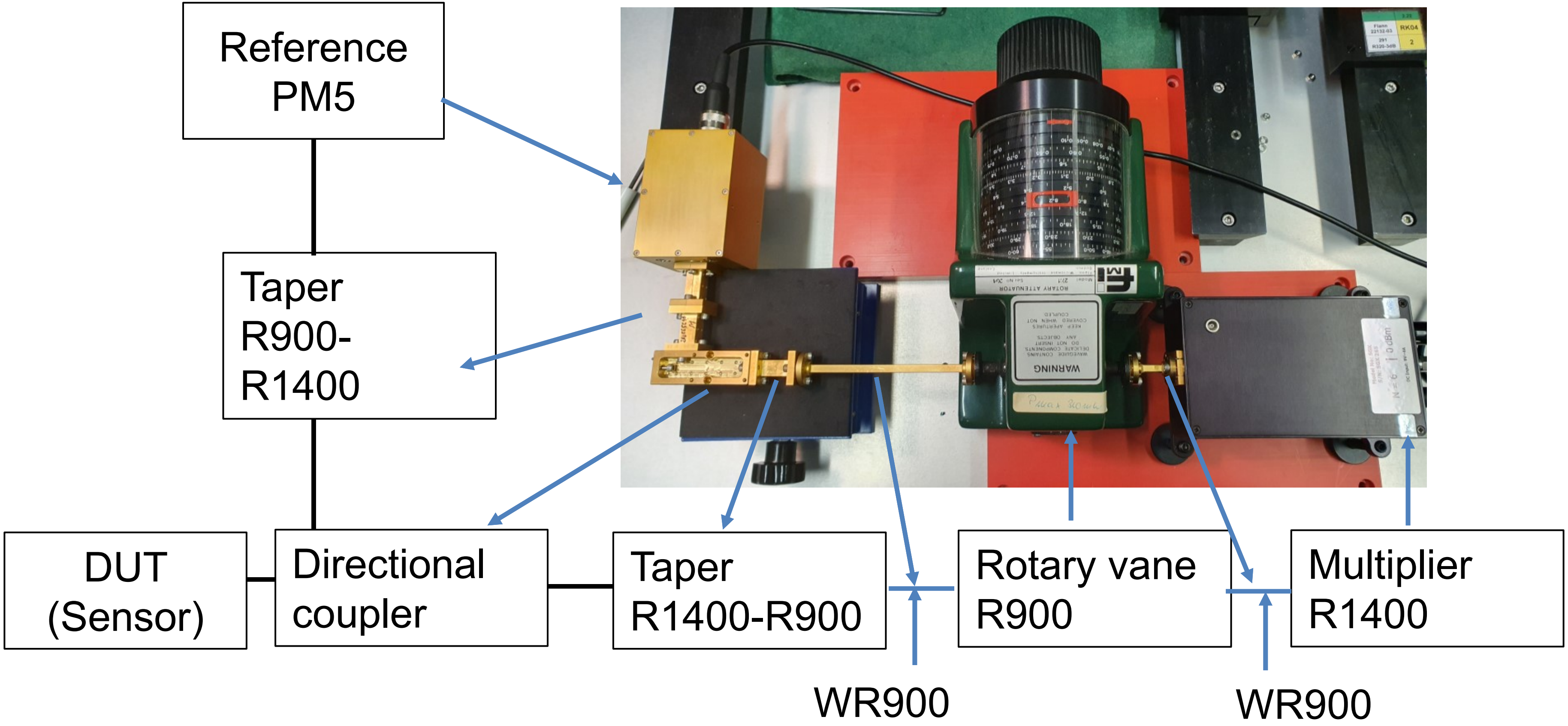
Multiple Offset Short Measurements

Averaging Pavg from the Short Measurements

Generalized Sensor Efficiency

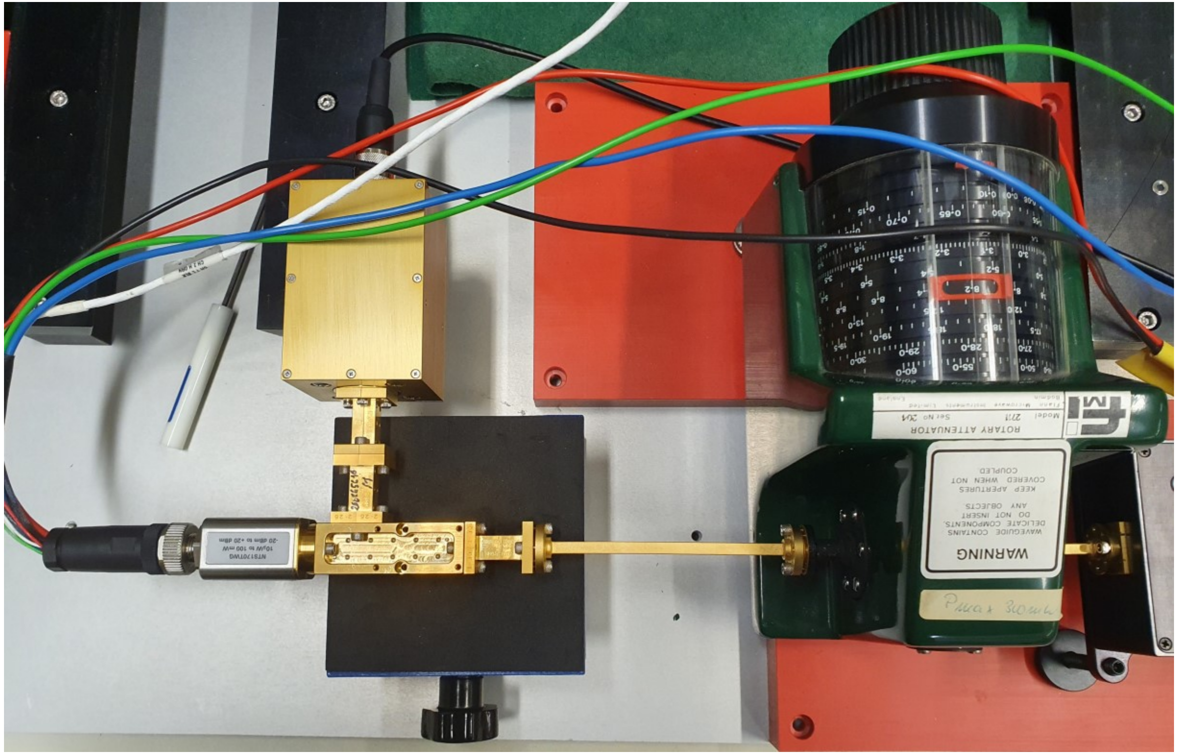
Direct Comparison Method

Measurement setup R&S sensors

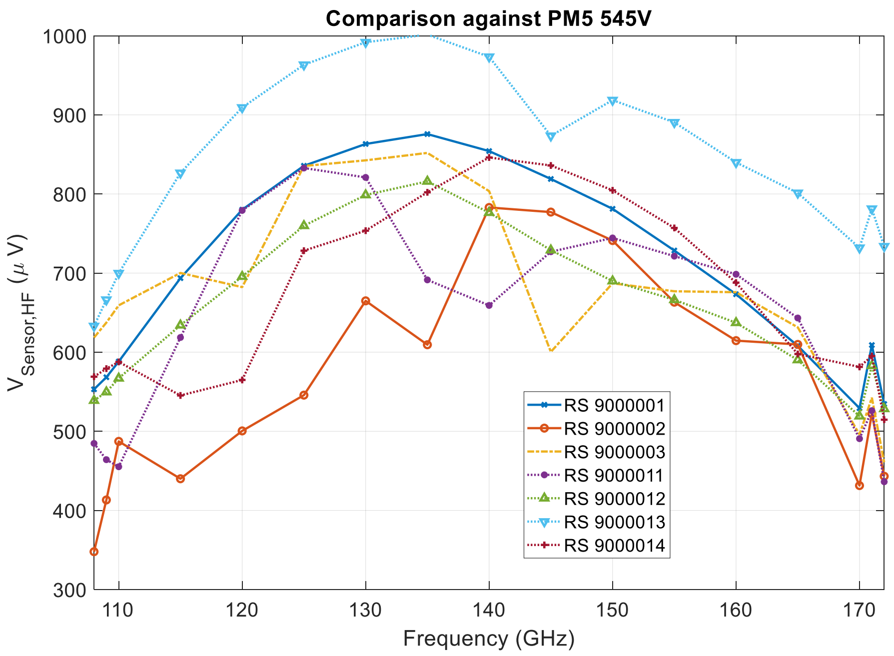


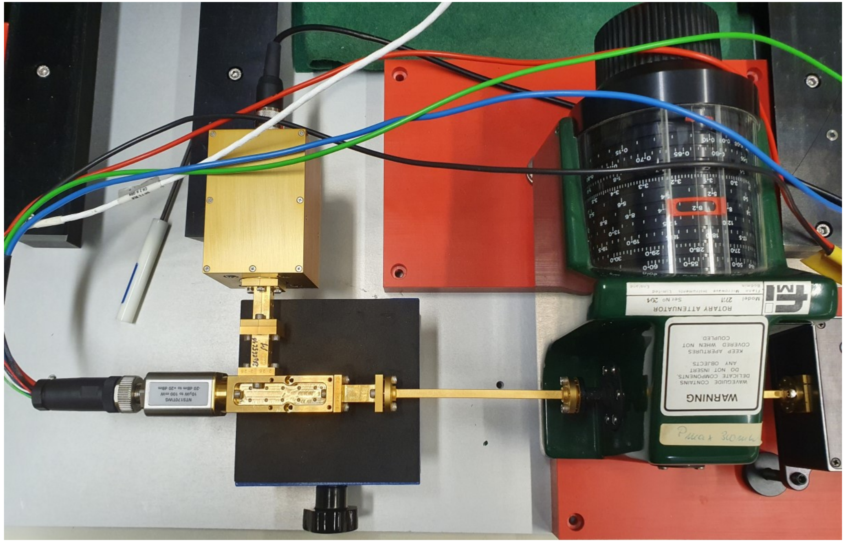
Measurement of R&S Thermoelectric Sensors

R&S-Sensor
900001
900002
900003
900011
900012
900013
900014

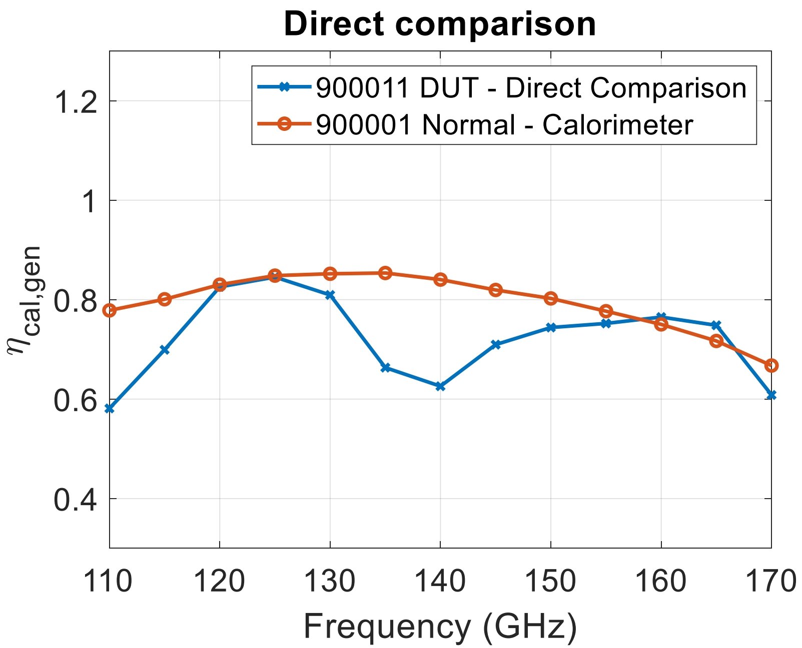


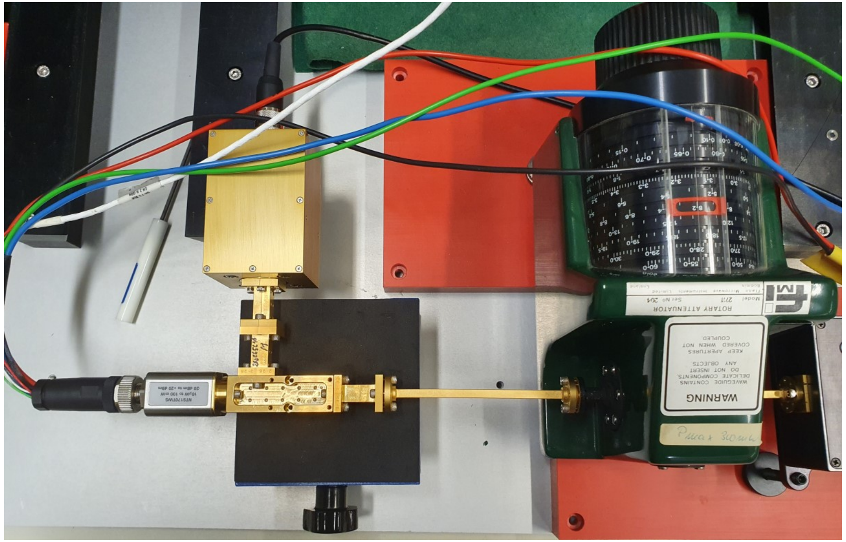
Raw Measurement Data





Direct Comparison Results





$$\eta_{cal,X} = \eta_{gen} \cdot \frac{P_{N,Ref}}{P_{x,Ref}} \cdot \frac{U_{TS,X}^2}{U_{TS,N}^2} \cdot \frac{R_{TS,N}}{R_{TS,X}} \cdot \frac{\left(1 - \left|\Gamma_{TS,N}\right|^2\right)}{\left(1 - \left|\Gamma_{TS,X}\right|^2\right)} \cdot \frac{\left|1 - \Gamma_G \cdot \Gamma_X\right|^2}{\left|1 - \Gamma_G \cdot \Gamma_N\right|^2}$$

Summary and Conclusion

Summary and Conclusion

- State-of-the-art of RF power traceability:
  - So far, direct comparison and microcalorimeter measurement for thermistors and thermoelectric power sensors established up to W-Band
- **New:**
  - **Waveguide calorimeter developed, manufactured and characterized up to 170 GHz**
  - **Direct comparison method at D-Band established for RF power calibration**
  - **Novel thermoelectric transfer standard, 1st prototype available**
  - **First results demonstrated reasonable**
  - **On-going work:**
    - **Establishing RF power traceability at D-Band**
    - **Extension to higher frequency range up to G-Band (140 GHz - 220 GHz) and J-Band (220 GHz - 325 GHz)**

Acknowledgement

Acknowledgement

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  - Florian Rausche

- Rohde & Schwarz:
  - Werner Perndl

Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
Bundesallee 100
38116 Braunschweig

Gia Ngoc Phung
Telefon: 0531 592-2226
E-Mail: gia.phung@ptb.de
www.ptb.de

Design of D-Band Thin-Film Power Sensor

Milan Salek, Yi Wang
Emerging Device Technology Research Group, Department of Electronic, Electrical and Systems Engineering
The University of Birmingham

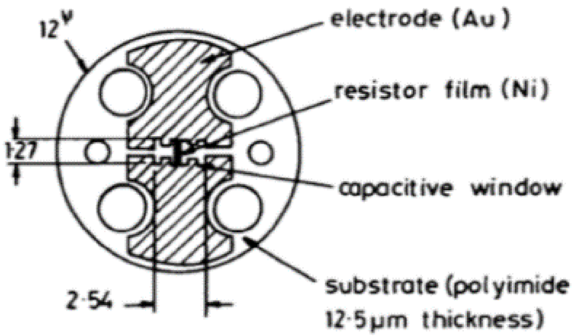
21 July 2021

Content

- Part 1
  - Introduction to our approach
  - Matched load design
  - Sensor prototype
  - Measurements
  - Summary
- Part 2
  - D-band power measurement using the BHAM sensor (Murat Celep, NPL)

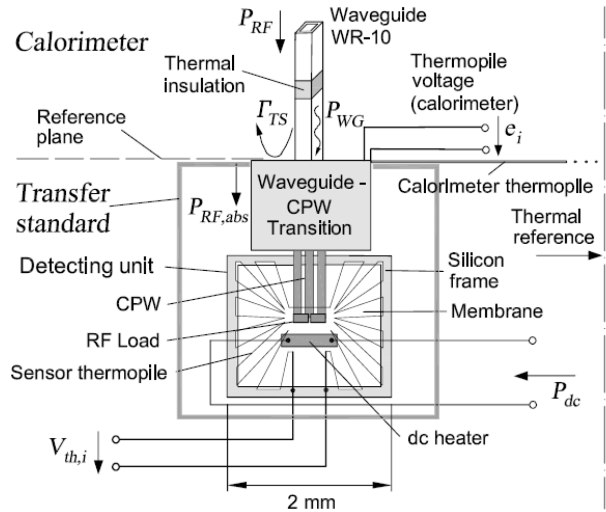
Power sensor structures suitable for sub-mm-Waves

UNIVERSITY OF BIRMINGHAM



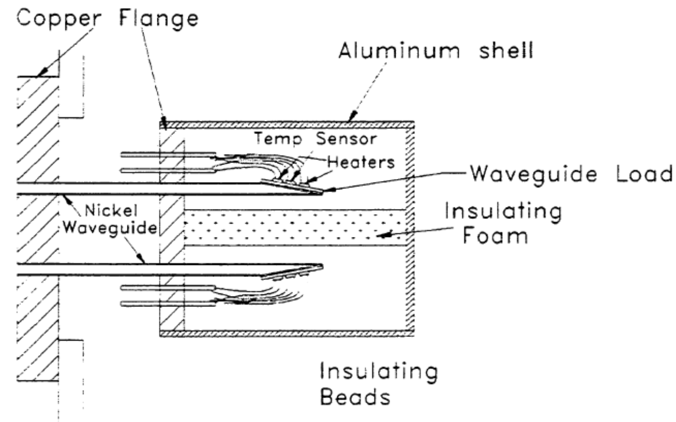
Thin film bolometer

T. Inoue, I. Yokoshima, and M. Sasaki, “High-Performance Thin-Film Barretter Mount For Power Measurement In W-Band,” *Electron. Lett.*, vol. 21, no. 5, pp. 170–172, 1985.



Thermoelectric sensor

R. H. Judaschke, K. Kuhlmann, T. M. Reichel, and W. Perndl, “Millimeter-Wave Thermoelectric Power Transfer Standard,” *IEEE Trans. Instrum. Meas.*, vol. 64, no. 12, pp. 3444–3450, 2015.



Matched load

N. Erickson, “A fast and sensitive submillimeter waveguide power meter”, 10th Int. Symp. Space Terahertz Technology, March 1999, pp. 501-507

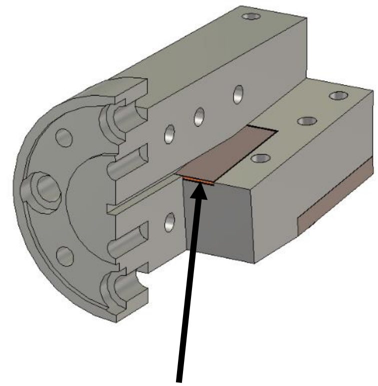
Our approach

Power sensor specification

- Frequency range of 110 - 170 GHz
- Operating resistance of thin film ~200 Ω

Approach

- Matched load to absorb RF power;
- Low-resistivity silicon substrate (RF absorber + ease of fabrication);
- Platinum line for sensing.



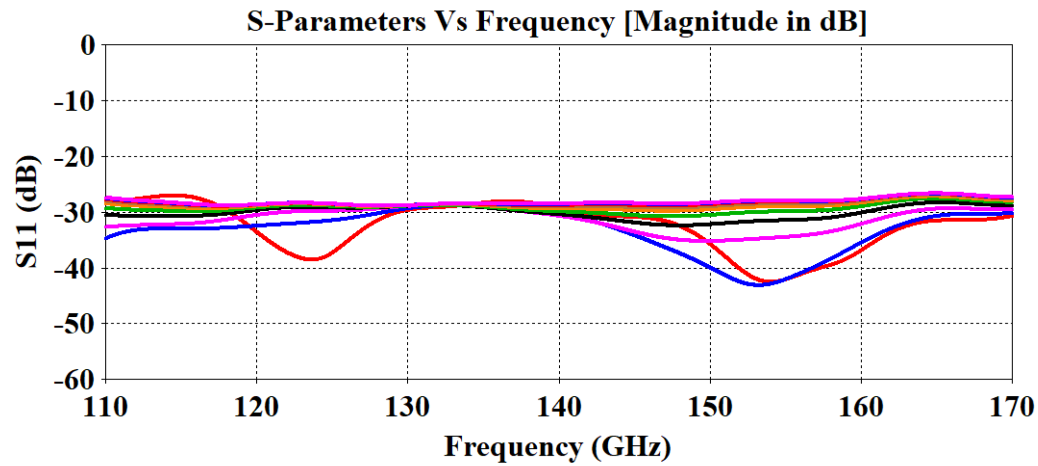
Main challenge

- Impedance matching (bandwidth, sensitivity to materials and fabrication tolerance)
- Sensor chip fabrication
- Thermal insulation

Matched load design

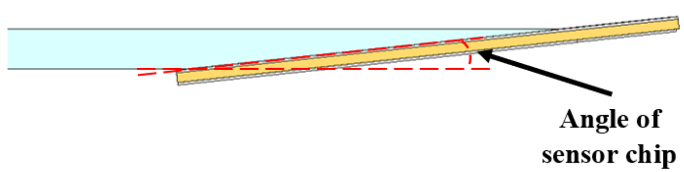
Conductivity of Si substrate

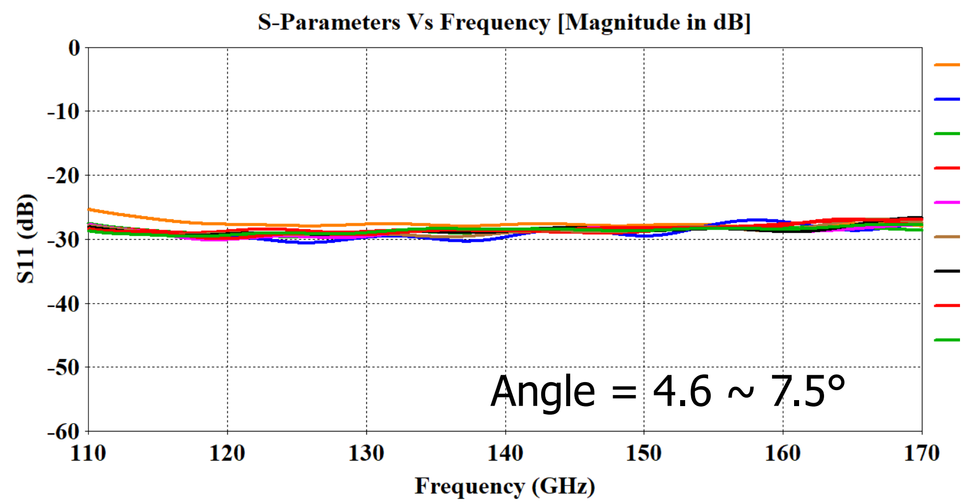
- S11 is under -28 dB when the electrical conductivity of silicon is 10 ~ 100 S/m (1 – 10 Ω·cm).
- Substrate thickness (100 - 600 um) has little effect on the matching.



Angle of the sensor chip

- When the angle is below 20°, S_{11} is below -20 dB across the D-band.

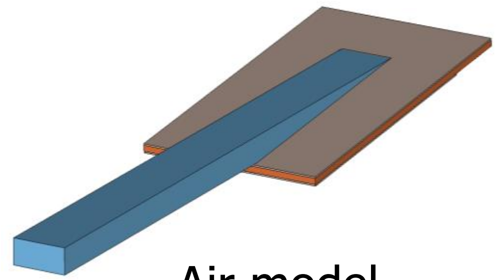


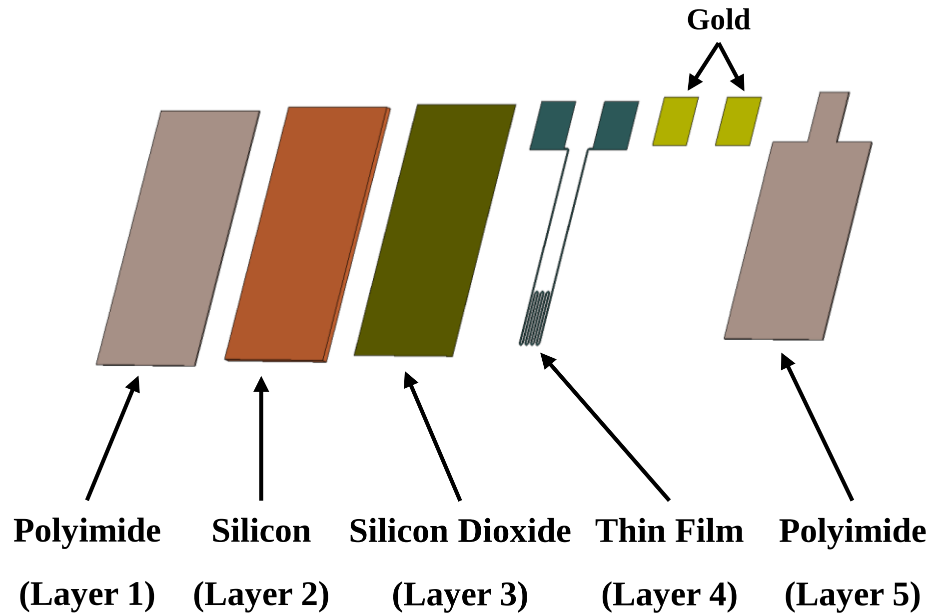


Thin-film sensor chip

- Polyimide (Kapton) thermal isolation layers: ~ 50 µm each
- Silicon substrate: ~ 200 µm
- Silicon dioxide (DC isolate silicon from platinum): ~ 1 µm
- Pt thin film: ~ 200 nm

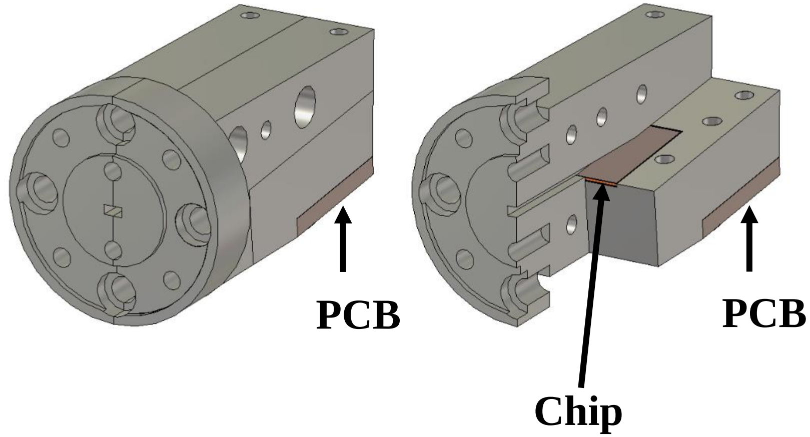
- The sensor chip is 10.4 mm × 5.65 mm.
- The meander thin-film line has a length of 30.5 mm and width of 80 µm.
- Each square gold pad has a side length of 2 mm.

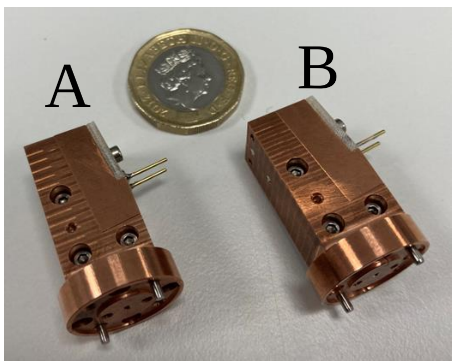


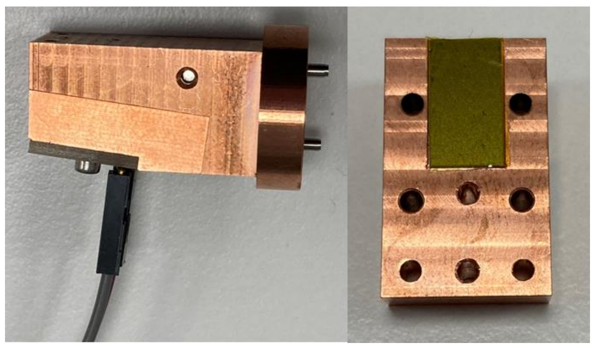


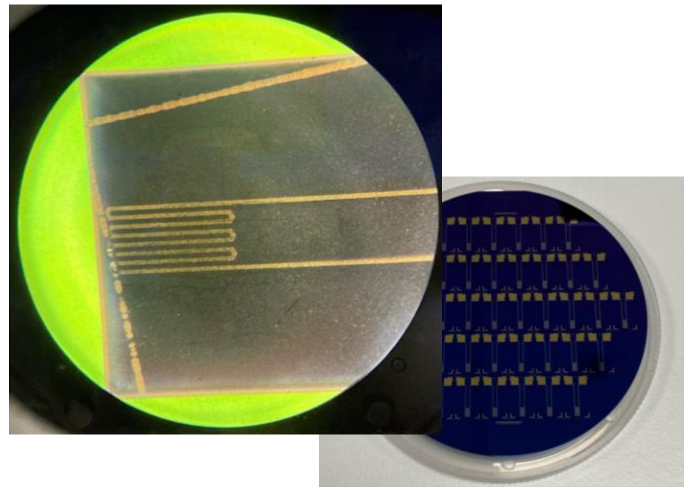
Sensor prototype

- Thermal isolation: two polyimide layers and air gap surrounding the chip (~100 µm).
- Electrical interconnection with DC: through spring loaded pin connectors.
- Housing: CNC machined from C109 tellurium copper
- Chip: fabricated at PTB; diced by a femtosecond laser cutter. DC resistance = 208.4 Ω (A) and 201.3 Ω (B).







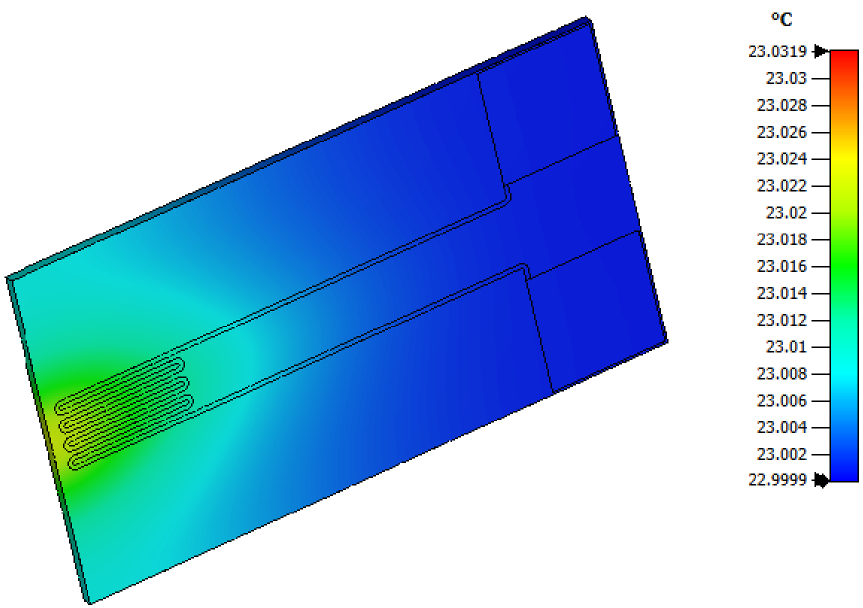


38 chips per 3 inch wafer

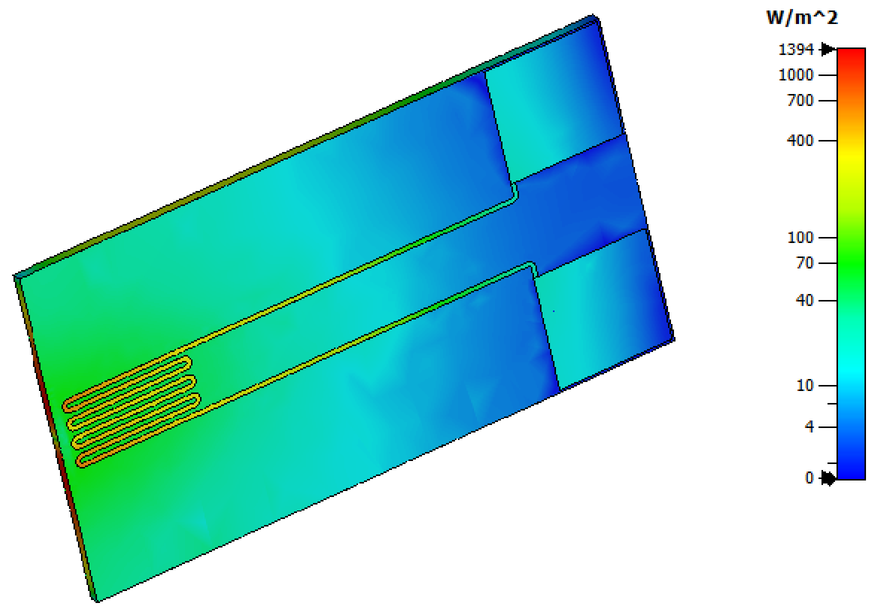
Thermal simulation

Assumption

- The RF power of 2 mW peak was used for thermal simulations.
- The ambient temperature is set at 23 ºC.

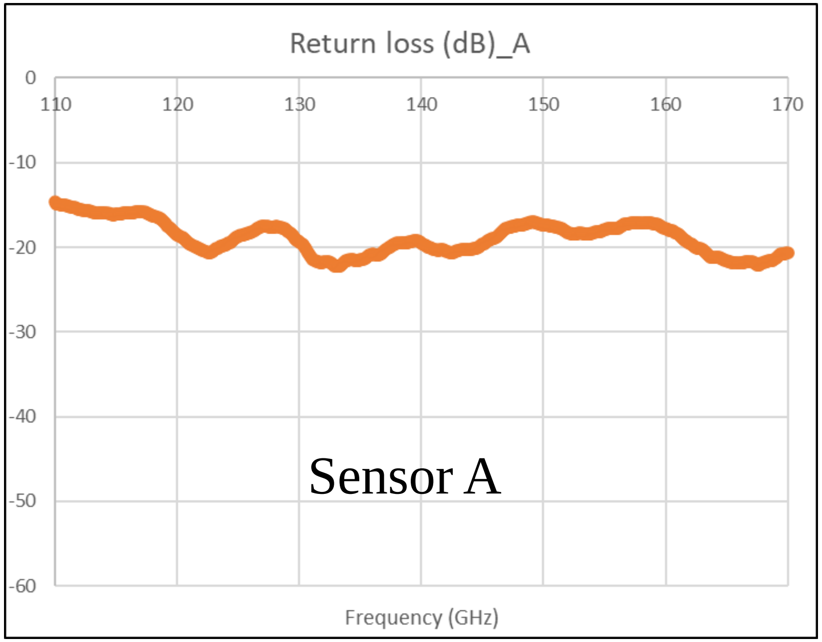


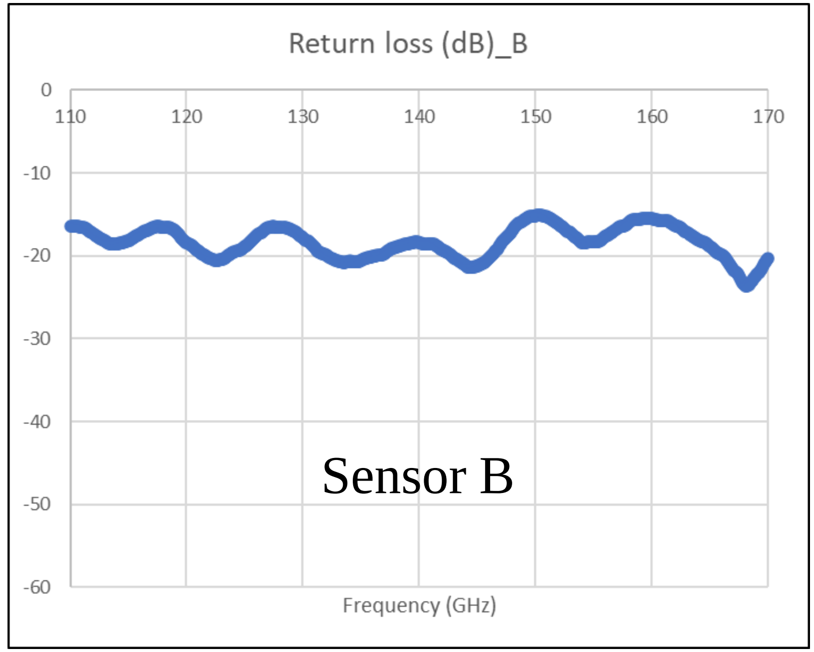
Temperature distribution



Heat flow

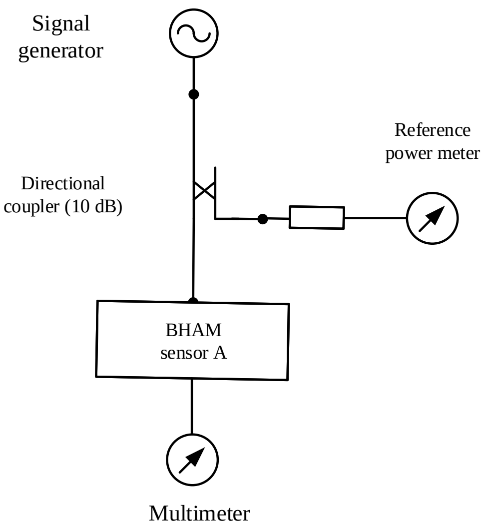
RF measurements

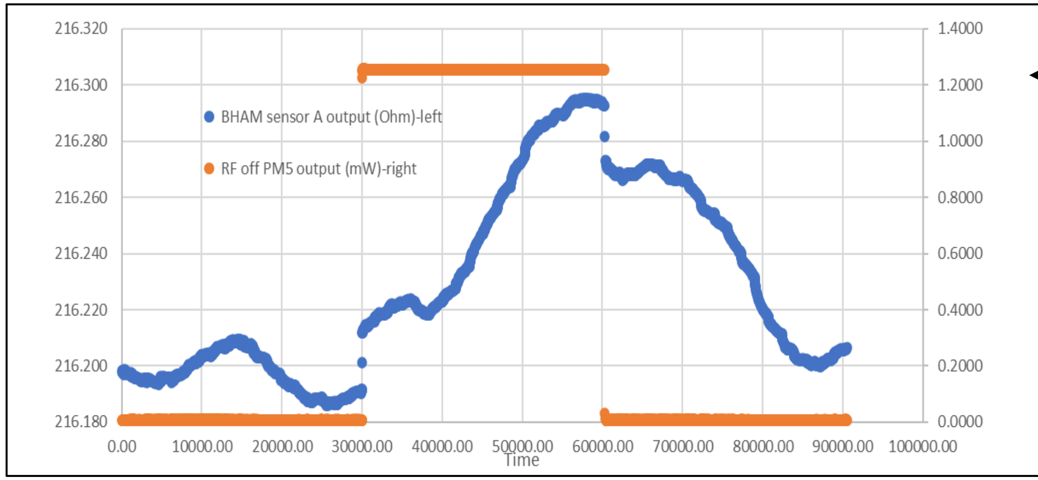




The measured return losses of both power sensors are consistent and over 15 dB across the band, lower than the 28 dB prediction from simulation.

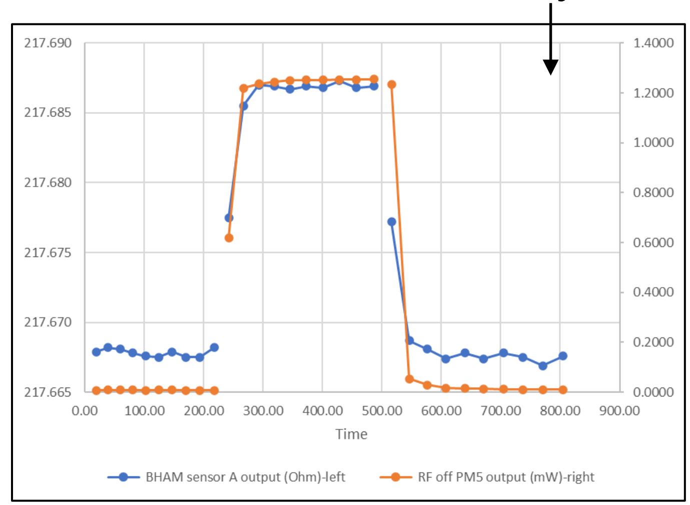
Sensor response in laboratory environment





Switch on and off every 20 min

Switch on and off every 4 s



- The response time is slow.
- The sensor response is significantly influenced by the environment.

⇩

Thermal insulation is not effective and reference temperature sensing is required!

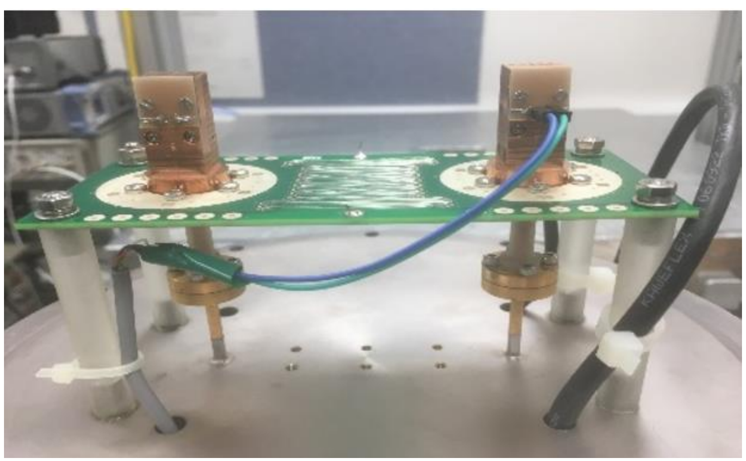
D-band power measurement using the BHAM microwave sensor

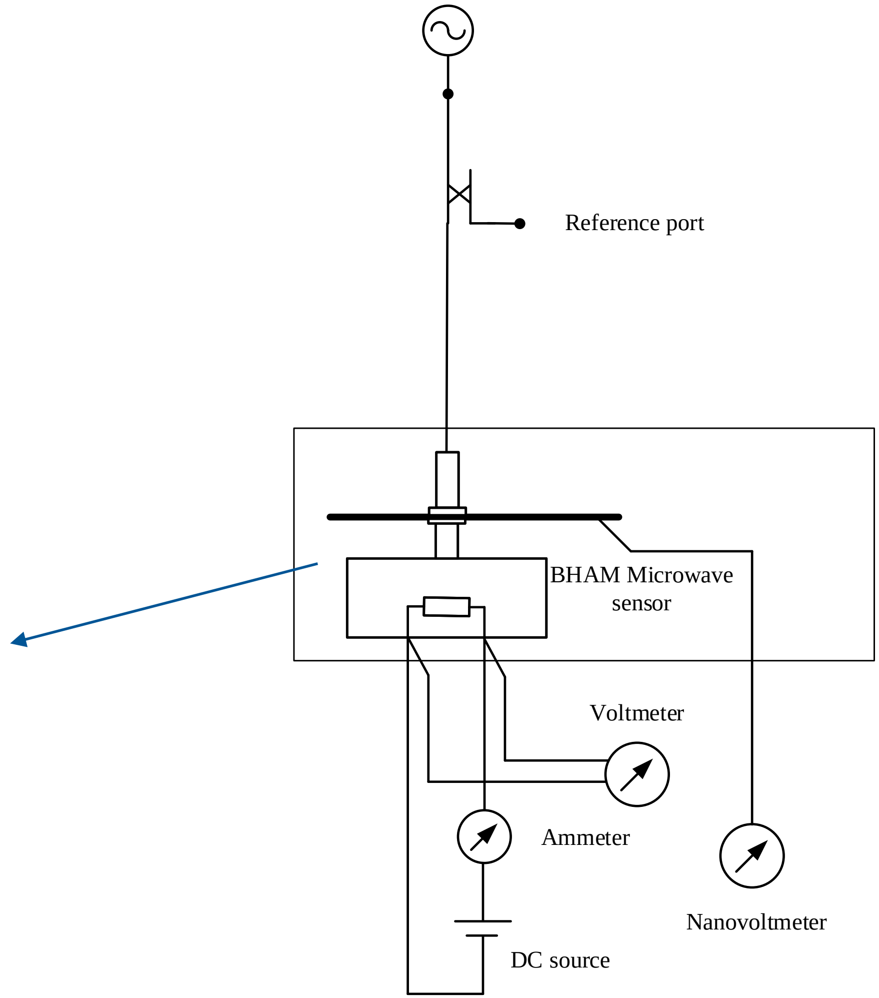
NPL National Physical Laboratory

Murat Celep

BHAM microwave sensor was attached to the D-band micro-calorimeter system.

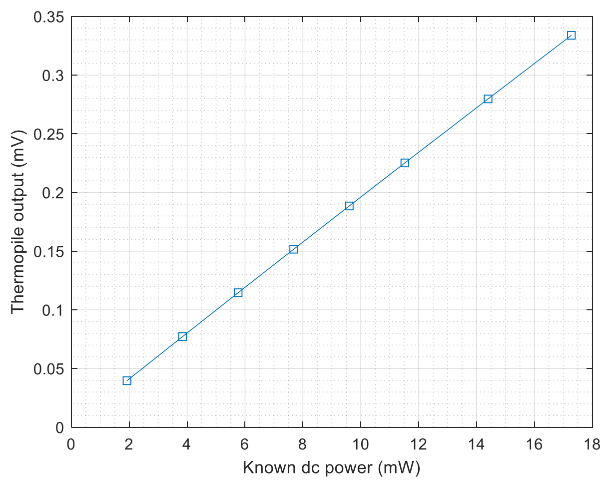
The system has been used to measure absolute microwave power.

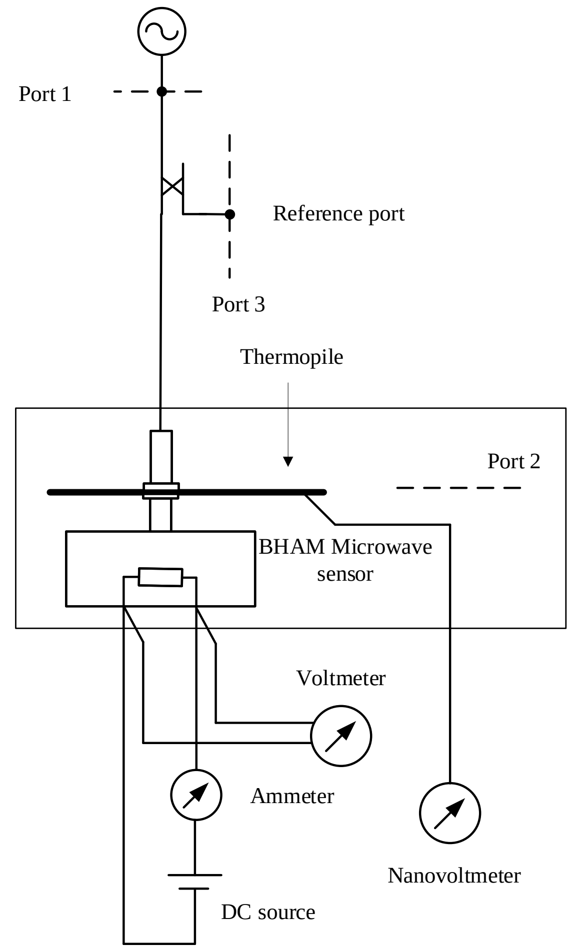




Calorimeter characterization

BHAM microwave sensor was connected to the micro-calorimeter and thermopile was characterized with BHAM sensor using DC known power (thermopile/BHAM sensor coefficient).

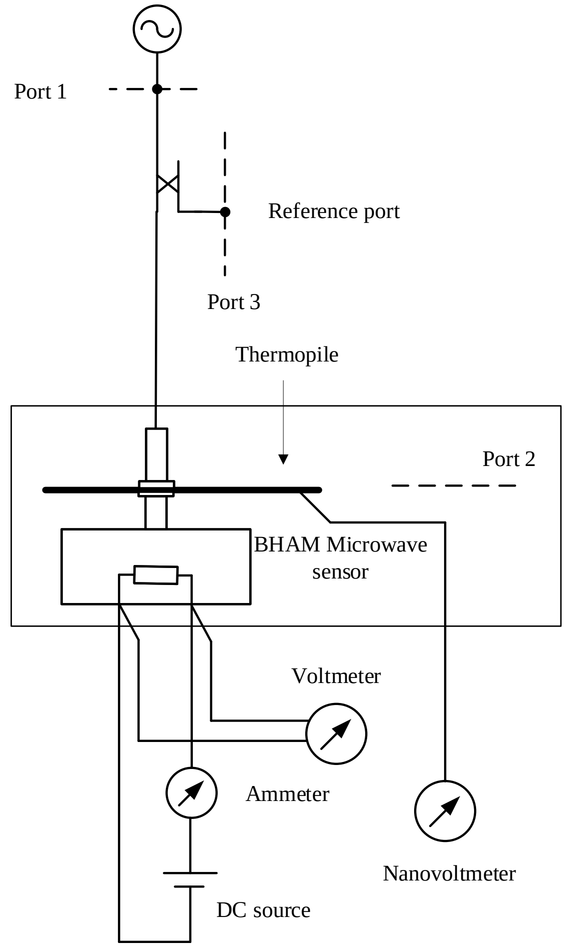




Calorimeter characterization

S-parameters of the calorimeter were measured for the 3-ports.

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix}$$



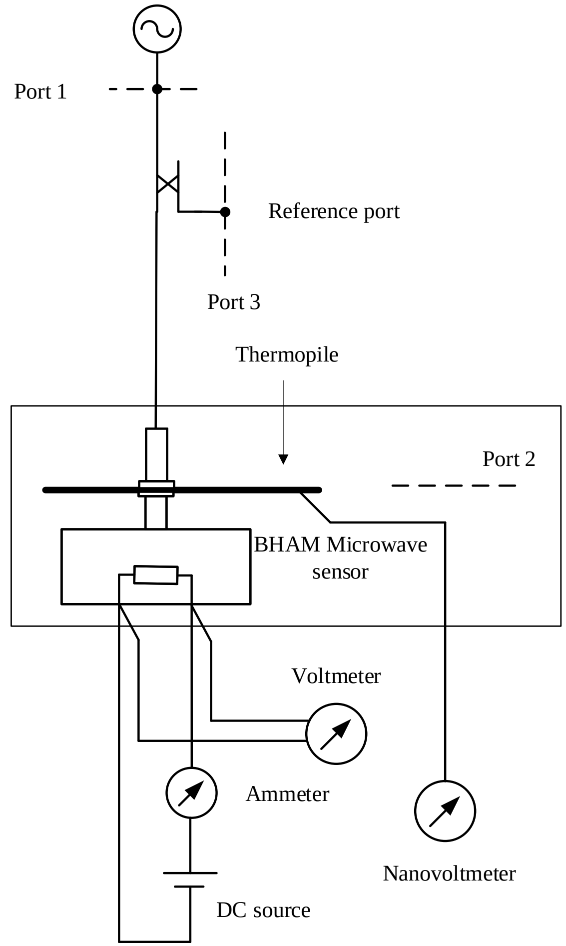
Microwave power measurement

DUT power meter (Erickson PM5) was attached to the reference port.

Microwave power was applied to the calorimeter port 1.

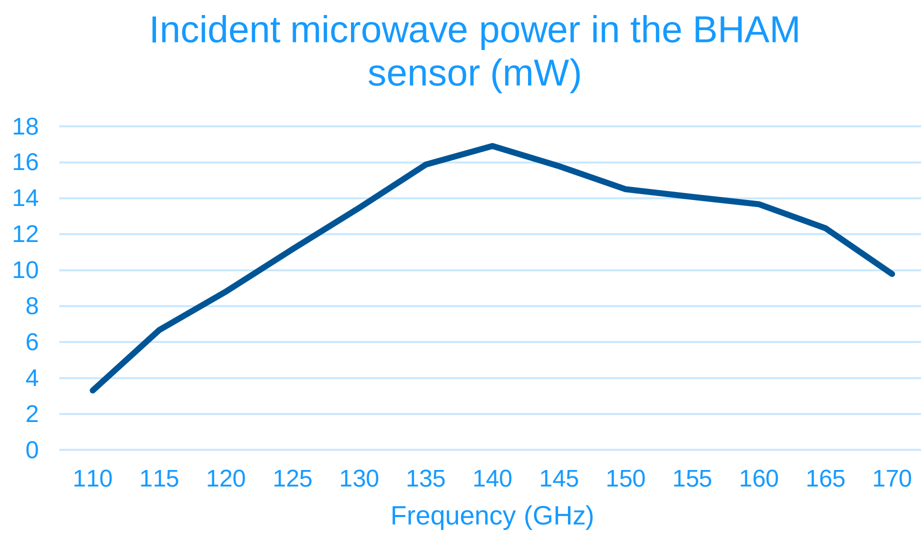
Heating effect of the dissipated microwave power on the BHAM sensor was measured through thermopile output voltage.

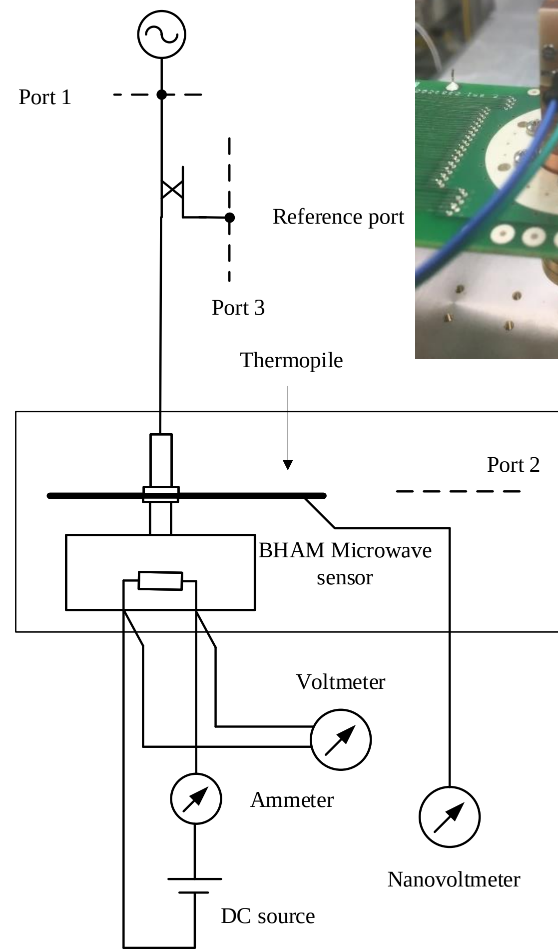
Output of the DUT power meter (P_{DUT}) was measured at the same time.

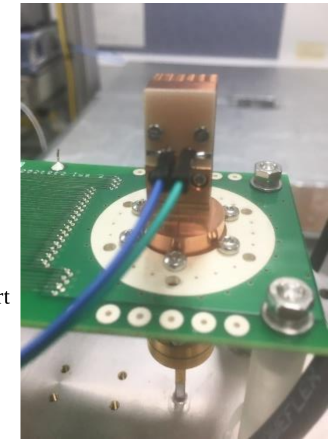


Microwave power measurement

Microwave incident power in the BHAM sensor (P_{mwd}) was calculated using thermopile/BHAM sensor coefficient.



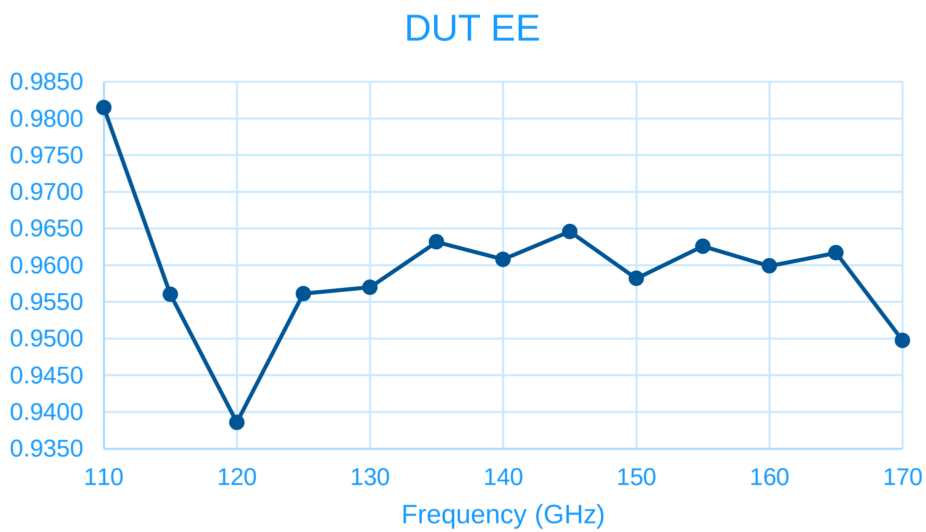




DUT effective efficiency

Effective efficiency of the DUT was calculated using below equation.

$$EE = \frac{P_{DUT}}{P_{mwd}} \frac{|S_{21}|^2}{|S_{31}|^2} \frac{1-|\Gamma_{STD}|^2}{1-|\Gamma_{DUT}|^2} \frac{|1-\Gamma_3\,\Gamma_{DUT}|^2}{|1-\Gamma_2\,\Gamma_{STD}|^2}$$



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THz broadband spectroscopy: instrumentation and performance

Mira Naftaly

- **Dielectric properties, quantities and units**
- Technologies for broadband dielectric measurements at THz and sub-THz frequencies
- Low-loss materials at THz and sub-THz frequencies

Dielectric properties, quantities and units

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"Dielectric" quantities

- Complex permittivity: $\varepsilon' + i\varepsilon''$
- Loss factor or tan-delta: $\tan\delta = \frac{\varepsilon''}{\varepsilon'}$

"Spectroscopic" quantities

- Absorption coefficient: $a\ [L^{-1}]$
- Extinction: k
- Refractive index: n

Conversion between quantities

National Physical Laboratory

$$k = \frac{c}{4\pi f}\alpha$$

$$\varepsilon' + i\varepsilon'' = (n + ik)^2 = (n^2 - k^2) + i\,(2nk)$$

$$n = \sqrt{\varepsilon' + k^2} = \sqrt{{}^{1}/_{2}\left[\varepsilon' + (\varepsilon'^2 + \varepsilon''^2)^{1/2}\right]}$$

$$k = \frac{\varepsilon''}{2n}$$

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{2nk}{n^2 - k^2}$$

Frequency and wavelength unit conversion

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Frequency (THz)	Wavelength (μm)	Wavenumber (cm^{-1})	Energy (meV)
ν	$\lambda = c/\nu$	$\sigma = \nu/c$	$eV = h\nu c/10^8$
1	299.8	33.35	4.136
299.8	1	10000	1240
0.02998	10000	1	0.1240
0.2418	1240	8.065	1

- Dielectric properties, quantities and units
- **Technologies for broadband dielectric measurements at THz and sub-THz frequencies**
- Low-loss materials at THz and sub-THz frequencies

Technologies for broadband dielectric measurements

- Time-domain spectroscopy
- Frequency-domain spectroscopy
- VNA-based spectroscopy
- Fourier transform spectroscopy

THz spectrometer instruments

Closed-loop

- TDS – Time-domain spectrometer (pulsed)
- FDS – Frequency-domain spectrometer (CW)
- VNA – Vector network analyser (CW)

➢ ***Coherent*** detection measures ***field amplitude and phase***

Open-loop

- FTS – Fourier transform spectrometer (CW)
- Scanning spectrometer – any combination of a tunable source and a broadband detector

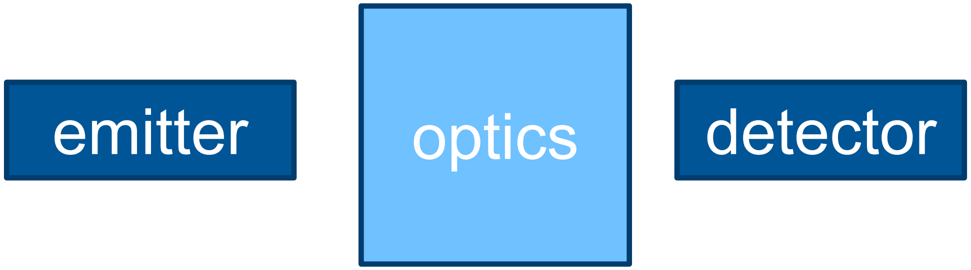
➢ ***Incoherent*** detection measures ***field intensity***

Coherent systems
strongly dominate broadband terahertz measurements

Open-loop and closed-loop systems

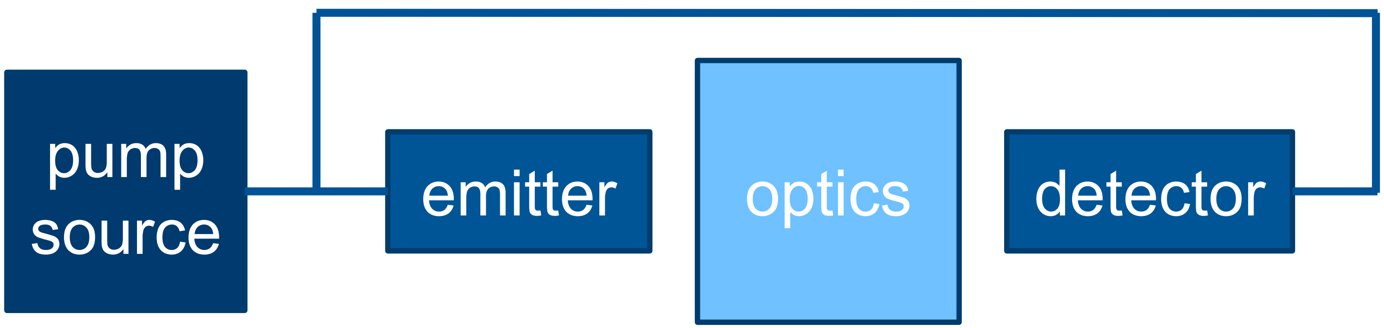
An open loop system consists of:

- an emitter and a detector **which operate independently;**
- optics to guide radiation from emitter to detector.



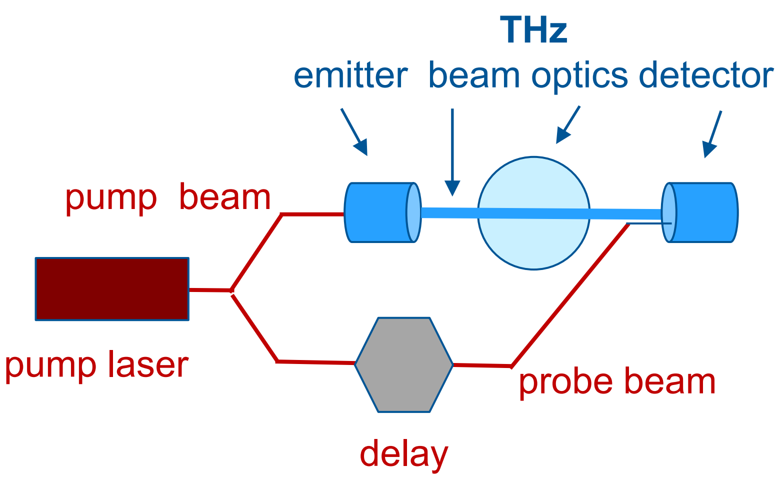
A closed loop system consists of:

- an emitter and a detector **which are activated by the same source;**
- optics to guide radiation from emitter to detector.



Time-domain spectrometer (TDS)

TDS is the dominant device for broadband THz measurements – accounting for >90% of published results.



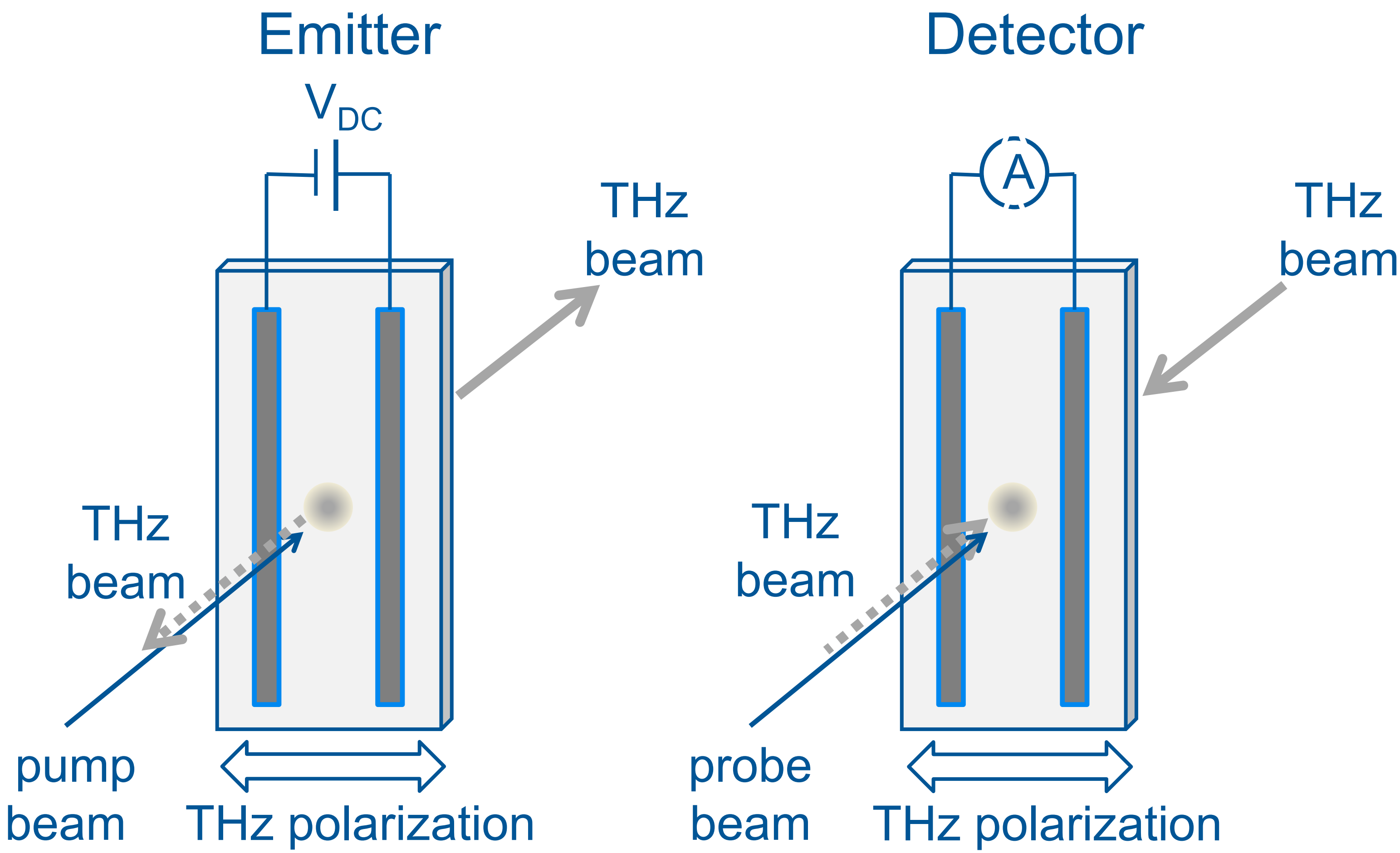
TDS performance

- **Broadband operation**
- **One-shot spectral acquisition**
- **Large bandwidth:**
  - **5-6 THz as standard**
  - **up to 20 THz is possible**
- **Frequency resolution 1-10 GHz**

TDS components:

- Pump laser – femtosecond pulsed
- Differential **variable** delay
- THz emitter – photoconductive antenna (most common)
- THz detector – photoconductive antenna (most common)
- THz beam guiding optics

Photoconductive THz emitters and detectors



Emitted beam is polarized **Detection is polarization sensitive**

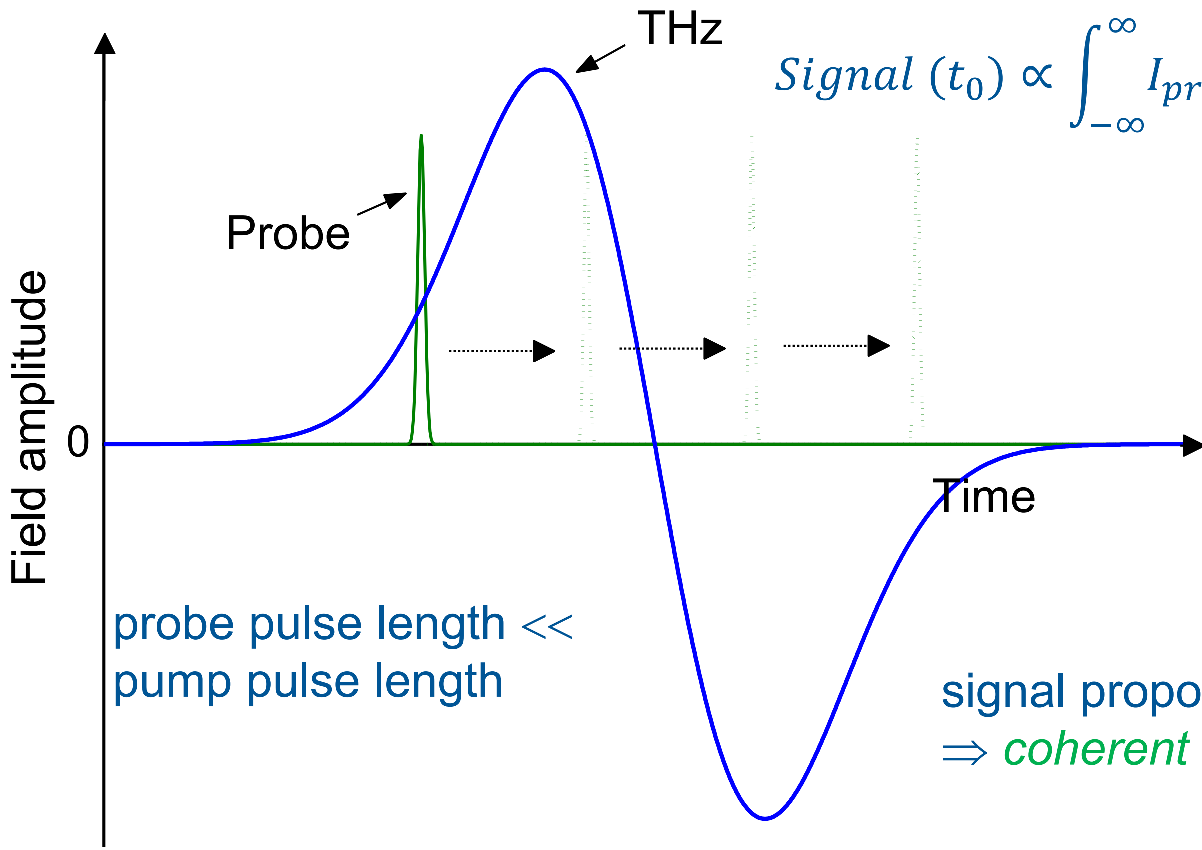
TDS operation

Uses a single-cycle THz pulse

Data is acquired in ***time domain***

by scanning the *probe pulse* over the *THz pulse* using *variable time-delay.*

$$Signal\ (t_0) \propto \int_{-\infty}^{\infty} I_{probe}(t - t_0)\, E_{THz}(t)\, dt$$



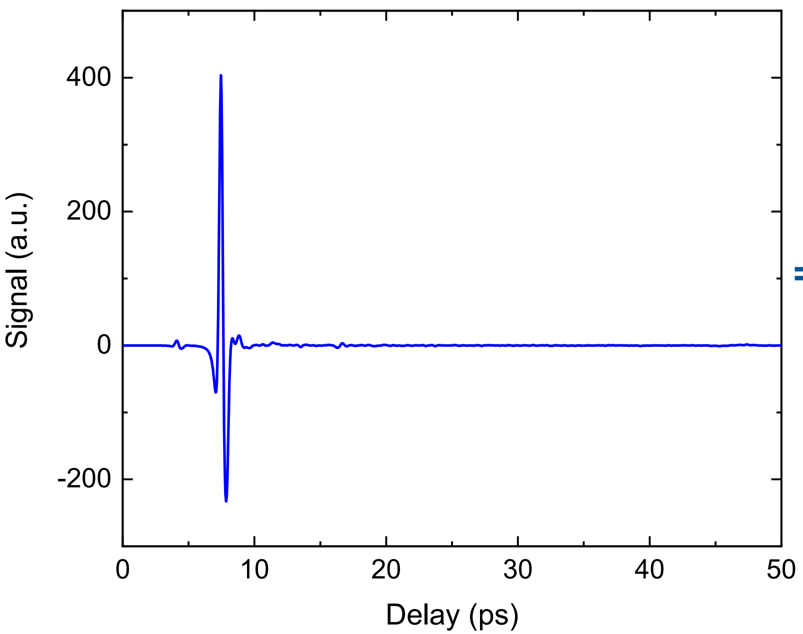
probe pulse length << pump pulse length

signal proportional to THz *field*
⇒ *coherent* detection

Spectral data from TDS

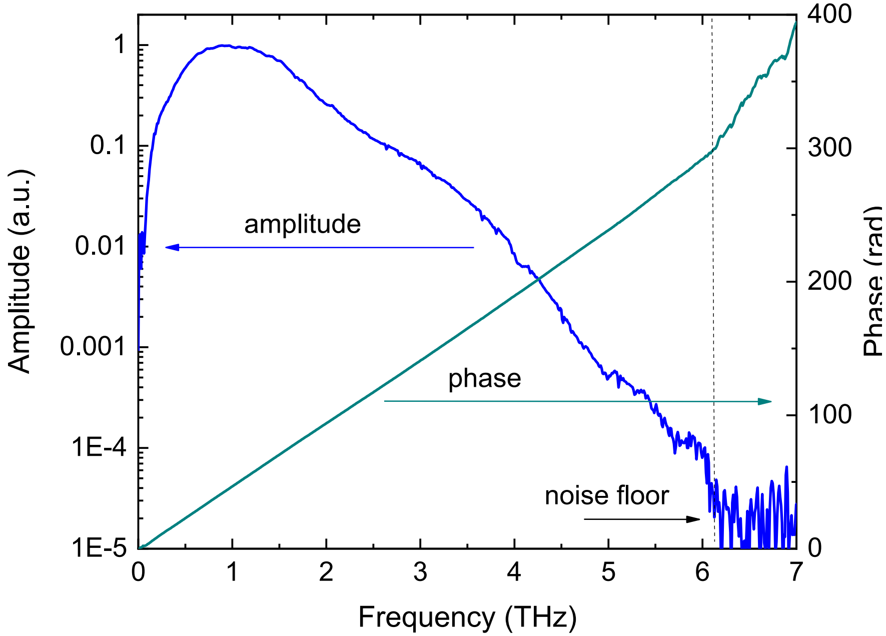
Amplitude and phase spectra obtained via Fourier Transform.

Time domain



FFT

Frequency domain



Parameter extraction in TDS

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Most TDS measurements are performed to obtain n & α !

Calculating **refractive index** and **absorption coefficient** of material from TDS data:

Field amplitude: E_{ref} & E_{sample}
Phase: ϕ_{ref} & ϕ_{sample}
Refractive index: n
Absorption coefficient: α [L^{-1}]
Sample thickness: d [L]

$$n(\omega) = 1 + \frac{(\phi_{ref} - \phi_{sample})\, c}{2\pi f d} \qquad (1)$$

$$T(\omega) = 1 - \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2} \qquad (2)$$

$$k(\omega) = \frac{\alpha c}{2\pi f} \qquad (3)$$

$$\alpha(\omega) = -\frac{2}{d} \ln\left(T \frac{E_{sample}}{E_{ref}}\right) \qquad (4)$$

Note: when k is non-negligible, Eqs. 2-4 must be calculated iteratively.

Example: lactose monohydrate

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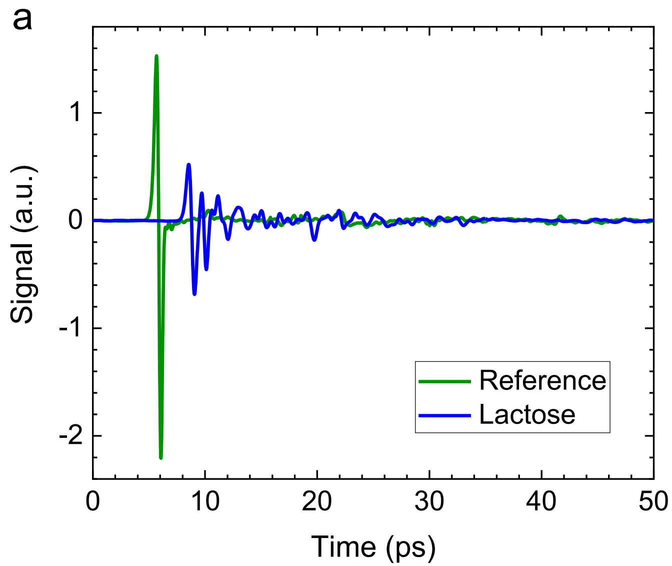
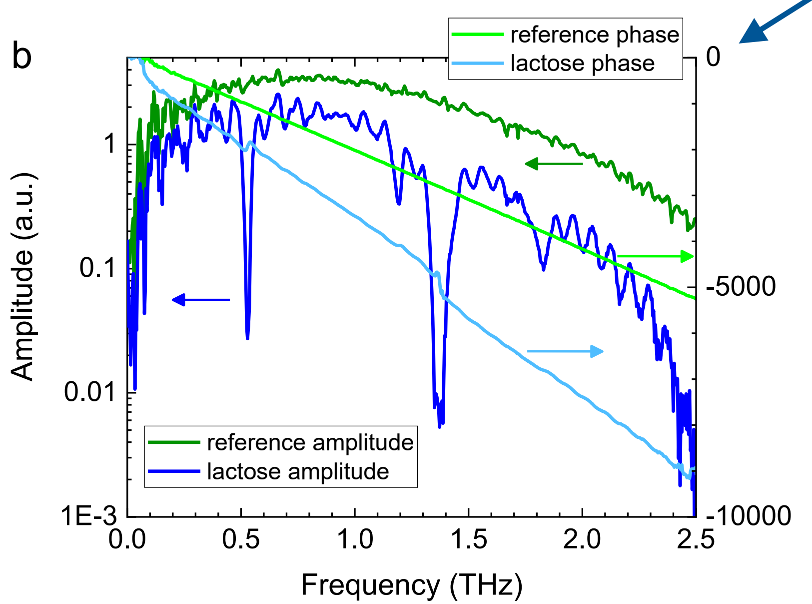
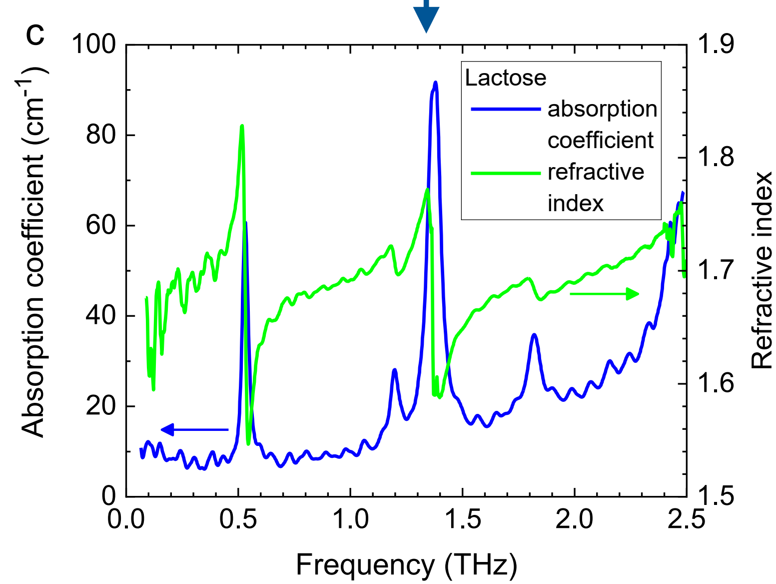


Time-domain data

Frequency-domain data (via FFT)

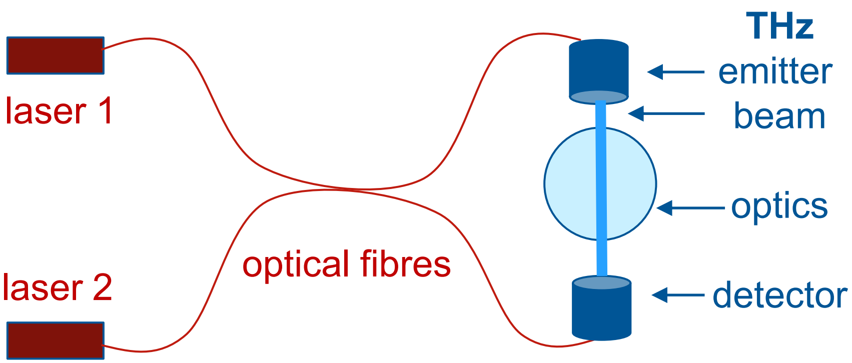
Calculated optical properties





Frequency-domain spectrometer (FDS)

FDS has a narrower measurement bandwidth than TDS, but has the advantage of much higher frequency resolution.



FDS performance

- **Broadband operation**
- **Frequency scanning**
- **Bandwidth: up to 3 THz**
- **Frequency resolution <50 MHz**

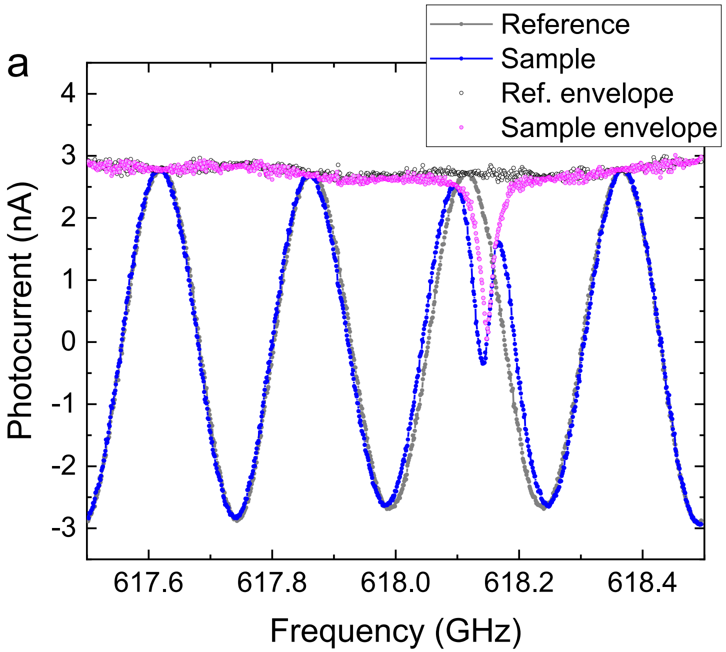
FDS components:

- Two stabilised CW lasers with offset wavelengths
  - THz is generated as the difference frequency
- THz emitter – photoconductive mixer
- THz detector – photoconductive mixer
- THz beam guiding optics

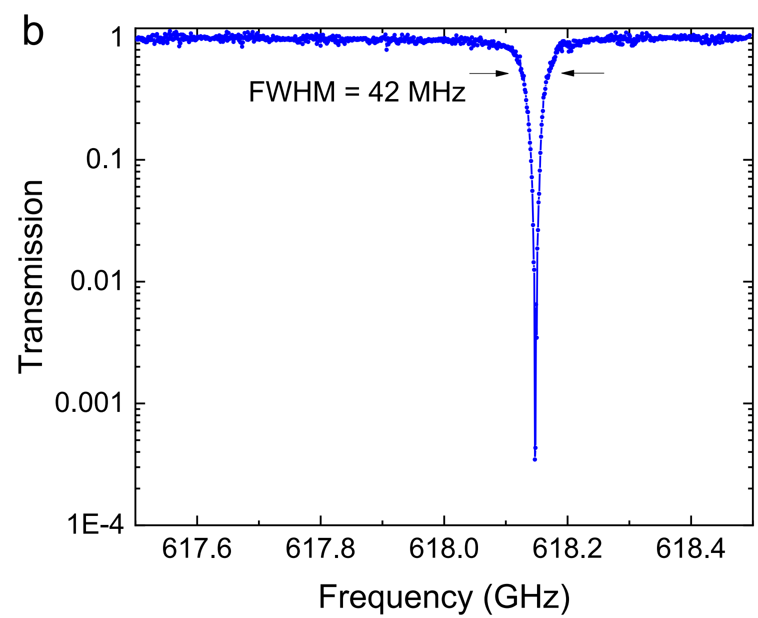
Example: whispering-gallery-mode resonance

Phase-sensitive (coherent) detection gives rise to **phase “fringes”** (these are not standing waves!)
Therefore an **envelope** function must be applied to the data.

Frequency-domain data



Calculated transmission



(Figure courtesy of Dominik Vogt, University of Auckland, New Zealand)

VNA-based FDS

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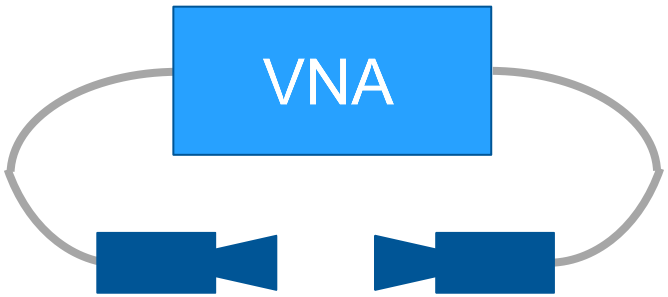
VNA-based spectrometers have a narrower measurement bandwidth than TDS or FDS, but higher frequency resolution.



extenders with horns

VNA performance

- **Frequency scanning**
- **Bandwidth: up to 1.7 THz**
- **Frequency resolution <0.1 MHz**

Components:

- VNA with frequency extenders
- Horn antennas or other optics
- **All-electronic**

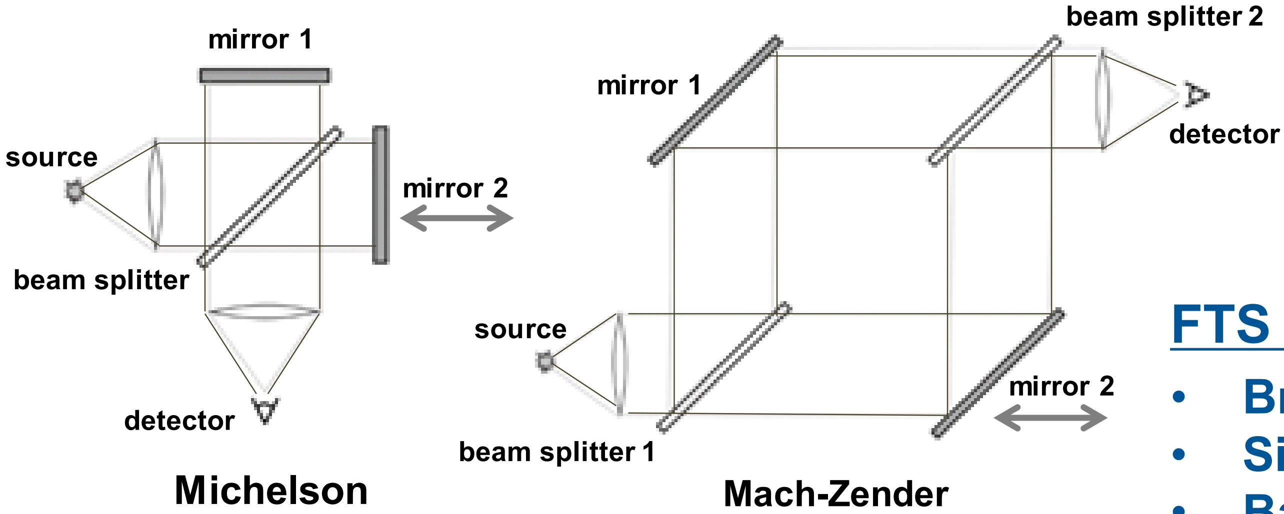
MCK by Swissto12

More information in other talks!

Fourier Transform Spectrometer (FTS)

FTS measures incoherently. It is an interferometric device.

Its major advantage is an extremely broad bandwidth.



FTS components:

- Broadband source (e.g. Hg lamp)
- Broadband power detector
- Optics
- Precision scanning mechanism

FTS performance

- **Broadband operation**
- **Single-scan full-spectrum**
- **Bandwidth:**
  - **1-180 THz standard**
  - **0.05-840 THz available**
- **Frequency resolution**
  - **1 GHz standard**
  - **<0.1 GHz available**

FTS operation

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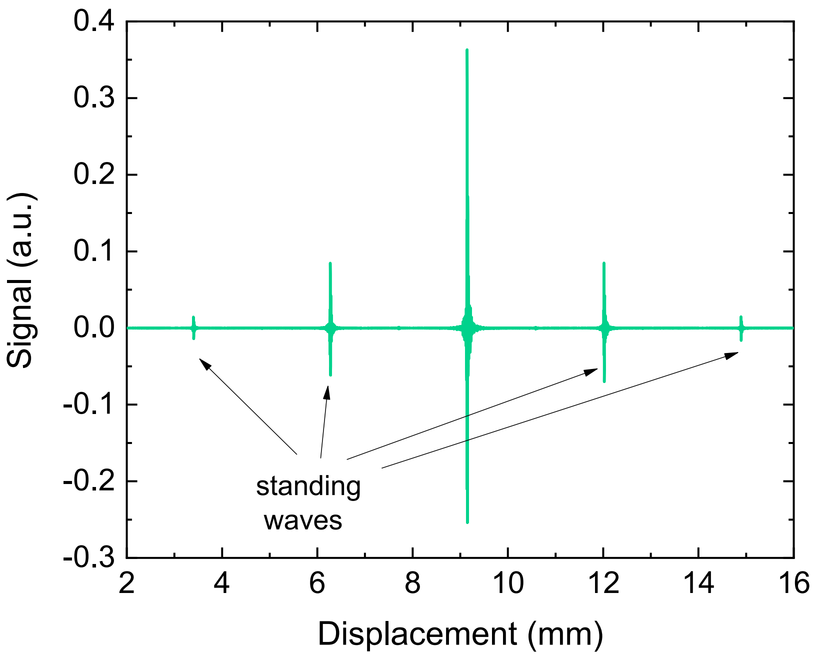
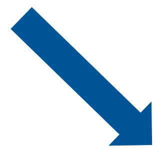
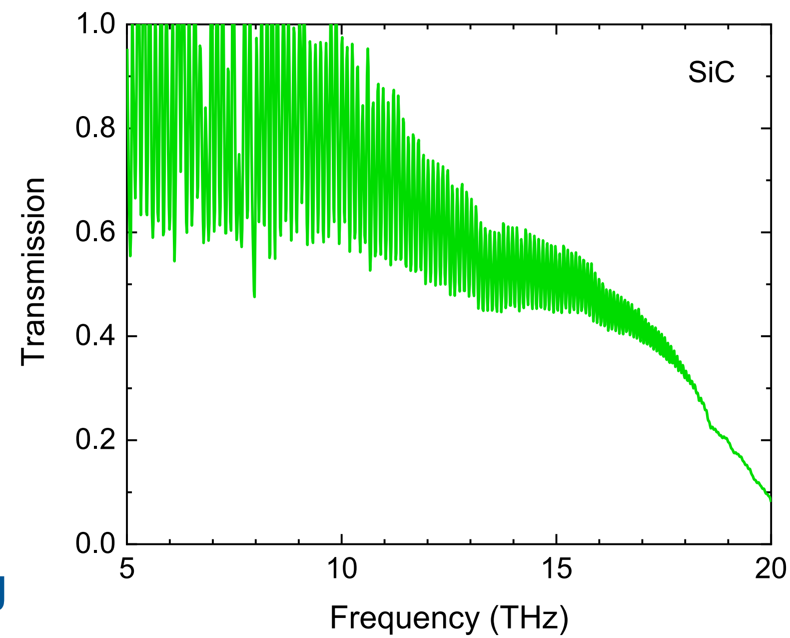
Data is acquired as an interferogram



FFT



Transmission is calculated by
1. applying FFT
2. dividing by reference



- Oscillations are etalon fringes due to standing waves in the sample.
- Fringes disappear when the sample has strong absorption
- **Fringes are necessary for extracting refractive index and absorption**

Parameter extraction in FTS

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Step 1: *n* is extracted from the fringe spacing:

$\Delta f = c/2nd$ (ideal case)

Note: extracting n from fringe spacing is <u>non-trivial</u>!

Step 2: α is extracted from the etalon transmission function:

$$T(f) = I_T(f)/I_0(f) = \frac{1}{\mathcal{M}+\mathcal{F}\sin^2\beta d}$$

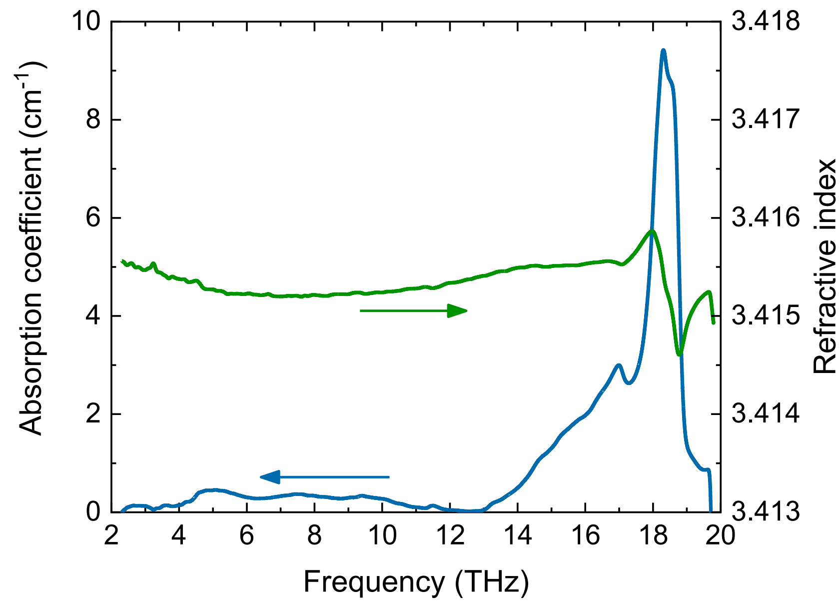
$$\mathcal{F}(f) = \frac{4R}{(1-R)^2}$$

$$\mathcal{M}(f) = \frac{\left(1-Re^{-2\alpha d}\right)^2}{(1-R)^2 e^{-2\alpha d}} > 1$$

$$R(f) = \frac{(n-1)^2}{(n+1)^2}$$

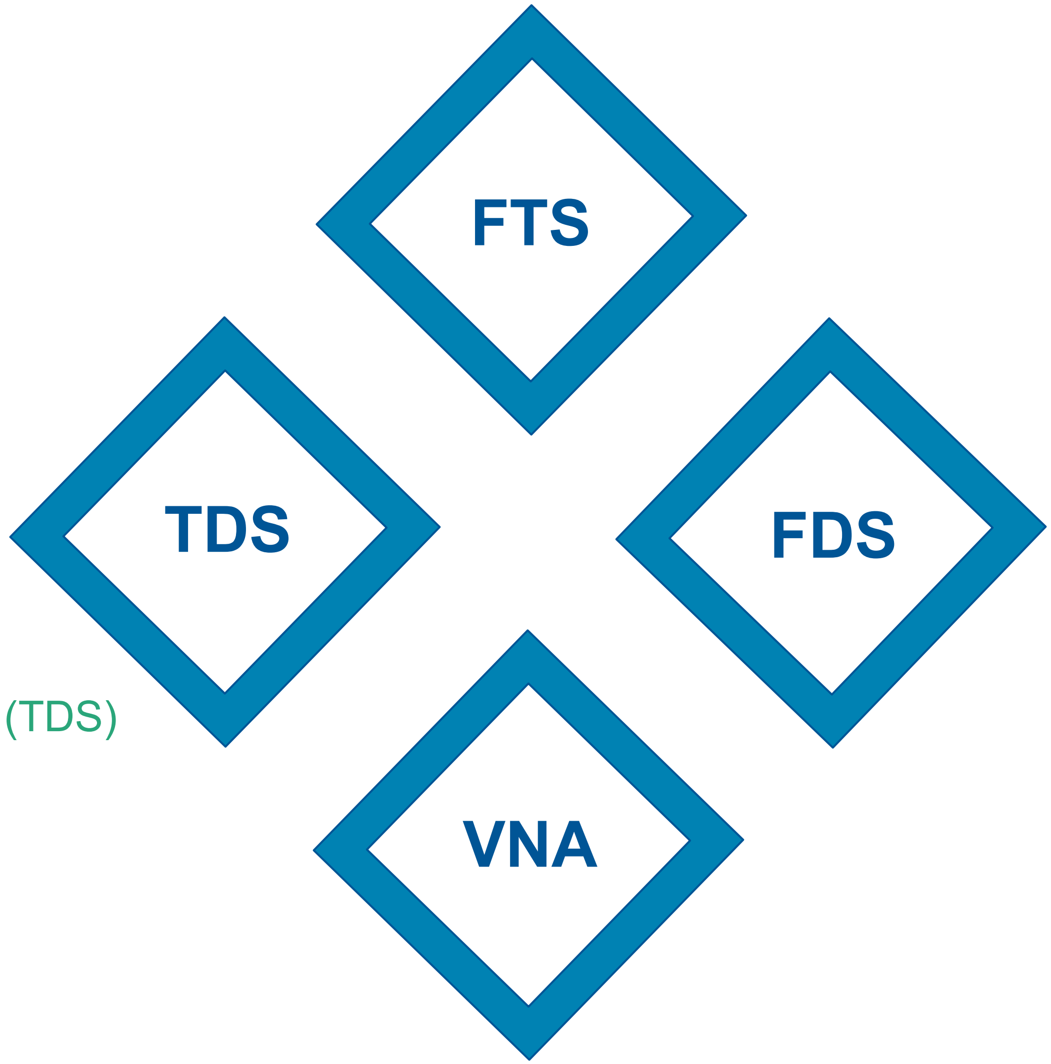
$$\beta = 2\pi f n/c$$

Example: high-resistivity Si



Parameter extraction in FTS is <u>not straightforward</u>, with many potential sources of error.
Samples must be sufficiently thin and low-loss to produce fringes.

Comparative advantages – a personal view



Criteria

Science

- Bandwidth (FTS)
- Frequency resolution (VNA)
- SNR & dynamic range (TDS, VNA)
- Unambiguous parameter extraction (TDS)
- Accuracy & precision

Industrial

- Speed of measurement
- Ease of measurement
- Repeatability
- Size of instrument
- Suitability for in-line applications
- Cost

- Dielectric properties, quantities and units
- Technologies for broadband dielectric measurements at THz and sub-THz frequencies
- **Low-loss materials at THz and sub-THz frequencies**

THz-transparent materials

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Few materials are THz-transparent!

- Inorganic crystals
- Non-polar polymers

Inorganic crystals

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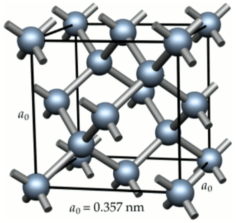
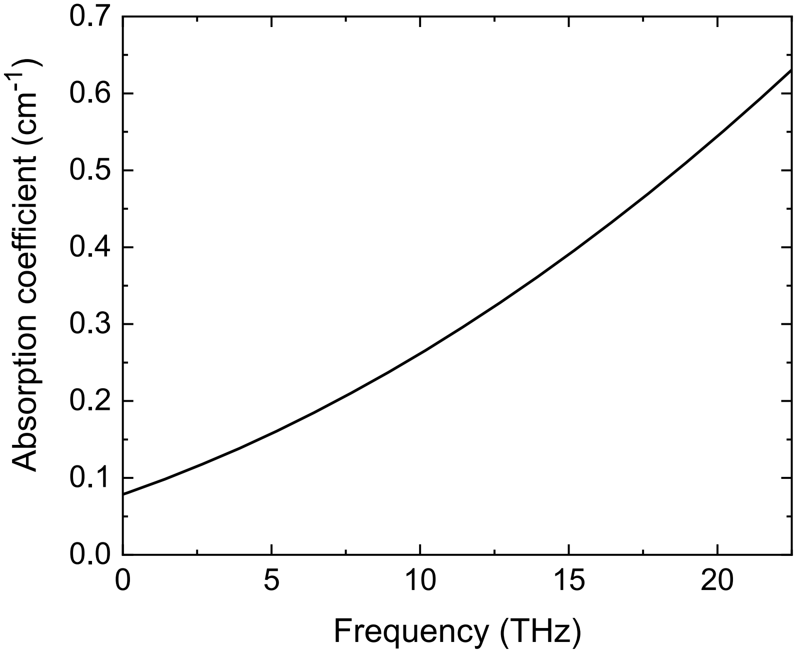
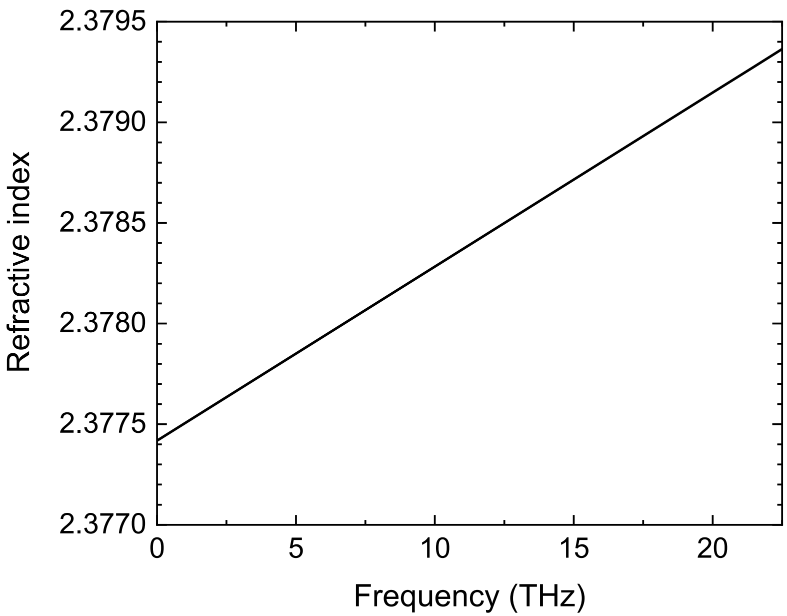
- Carbon group crystals
  - Diamond
  - High resistivity silicon
  - High resistivity germanium
  - Hexagonal silicon carbide
- Oxides
  - Quartz
  - Sapphire
- Nitrides
  - Aluminium nitride
  - Gallium nitride
  - Silicon nitride

Diamond C



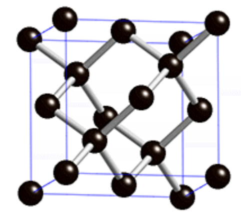
Crystal properties	Chemical formula Crystal type Crystal system	C Isotropic Cubic $Fd\bar{3}m$
Optical properties	Transparency (visible) Colour Birefringence Refractive index @ 590 nm Band gap eV	YES Colourless NO 2.4175 5.47
Physical properties	Density g/cm^3 Moh's hardness	3.515 10





Silicon Si

High resistivity (undoped)



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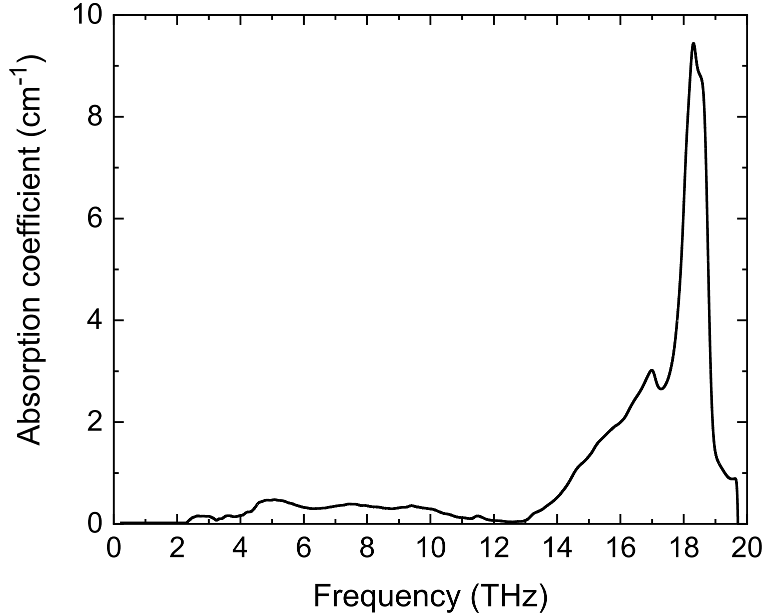
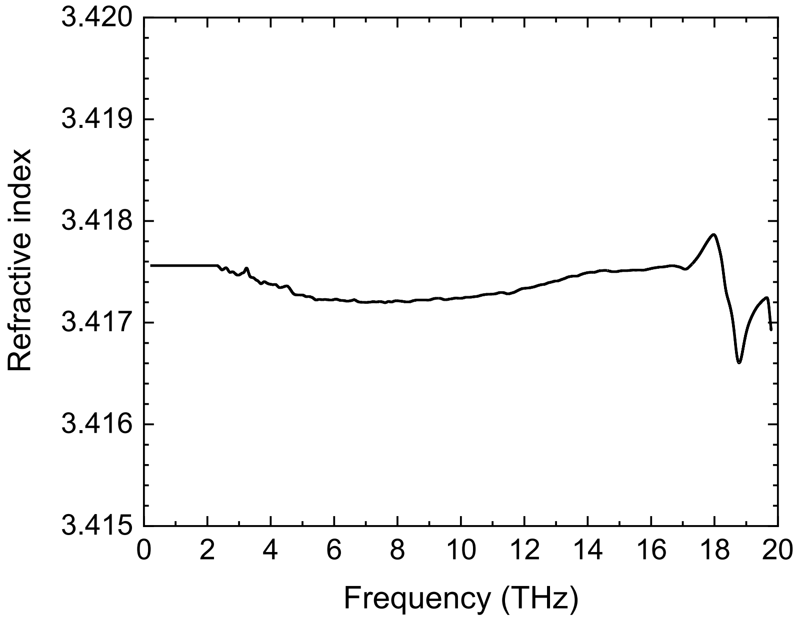
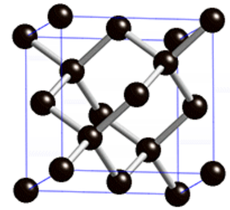
Crystal properties	Chemical formula Crystal type Crystal system	Si Isotropic Cubic $Fd\bar{3}m$
Optical properties	Transparency (visible) Colour Birefringence Refractive index @ 1.55 µm Band gap eV	NO Metallic grey NO 3.4777 1.12
Physical properties	Density g/cm^3 Moh's hardness	2.329 6.5





Germanium Ge

High resistivity (undoped)



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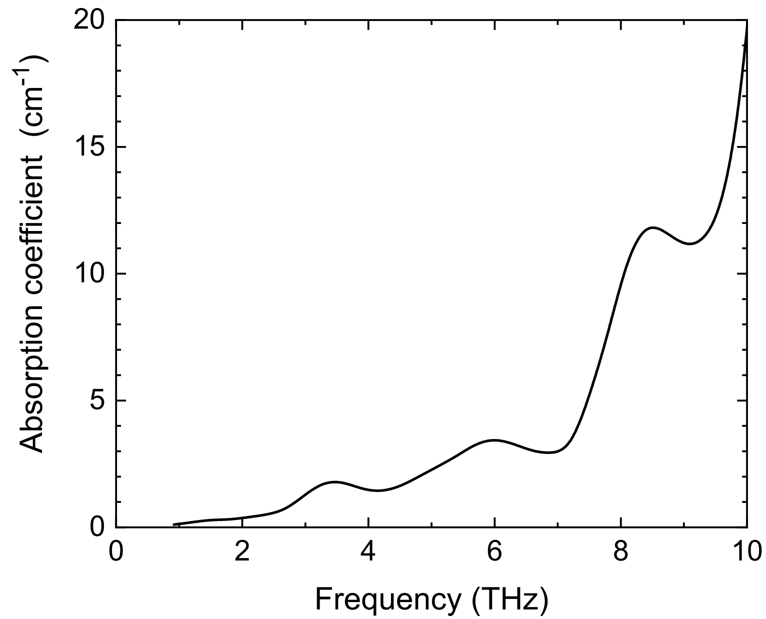
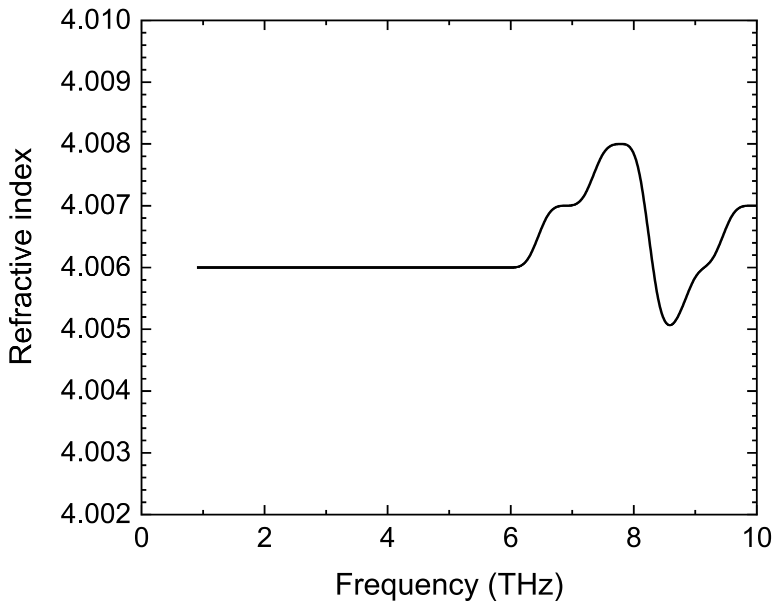
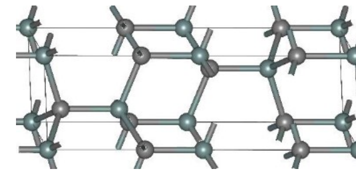
Crystal properties	Chemical formula	Ge
	Crystal type	Isotropic
	Crystal system	Cubic
		Fd$\bar{3}$m
Optical properties	Transparency (visible)	NO
	Colour	Metallic grey
	Birefringence	NO
	Refractive index @ 2.8 µm	4.052
	Band gap eV	0.66
Physical properties	Density g/cm^3	5.323
	Moh’s hardness	6.0

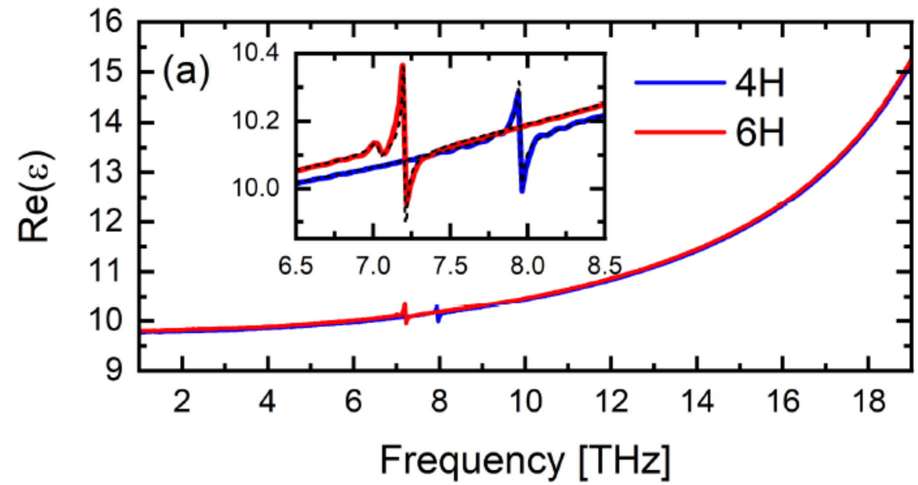


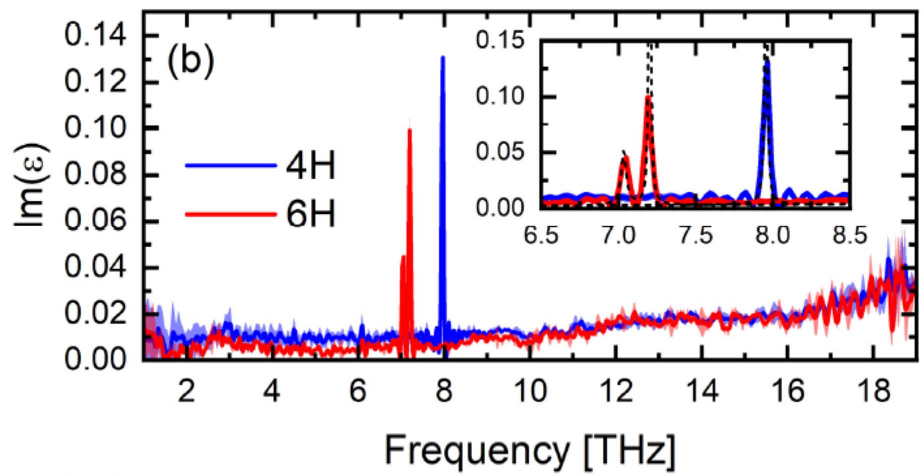


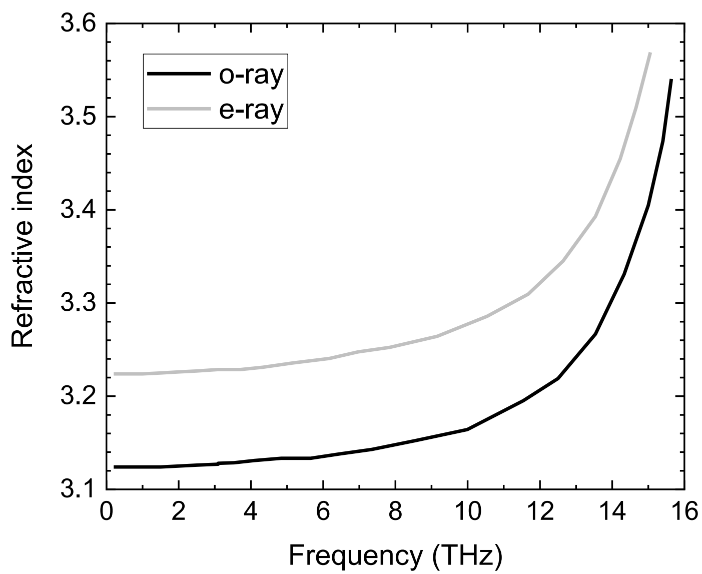
Hexagonal silicon carbide SiC



Crystal properties	Chemical formula	SiC
	Crystal type	Uniaxial
	Crystal system	Hexagonal
		C^4_{6v}-$P6_3mc$
	Polytypes	4H-SIC; 6H-SIC
Optical properties	Transparency (visible)	YES
	Colour	Colourless
	Birefringence	YES
	Refractive index @ 590 nm	o – 2.56
		e – 2.60
	Band gap eV	3.23 (4H); 3.05 (6H)
Physical properties	Density g/cm^3	3.21
	Moh's hardness	9.5

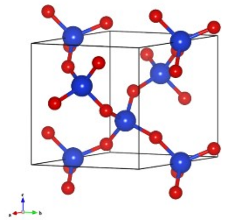




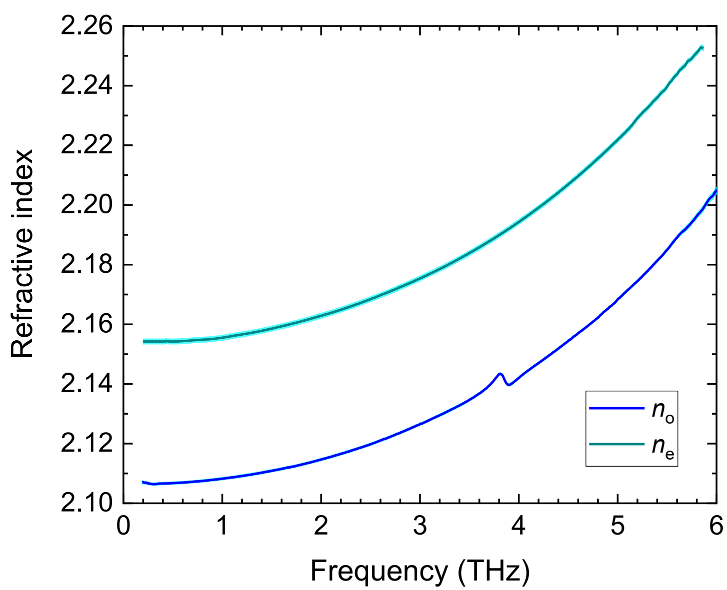


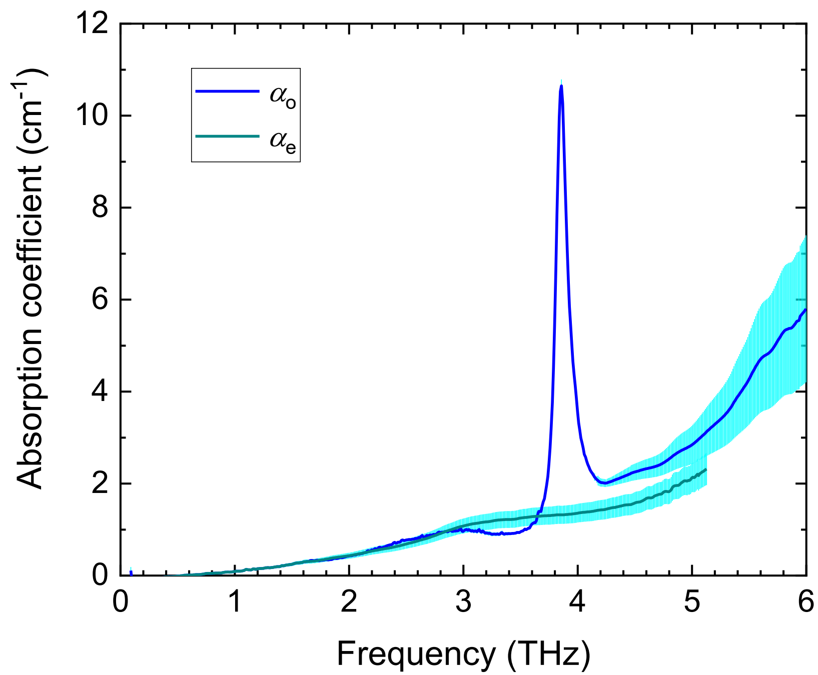
Tarekegne et al. *Optics express* 27 (2019): 3618-3628.

Quartz SiO_2

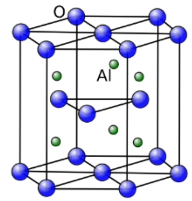


Crystal properties	Chemical formula Crystal type Crystal system Polytypes	SiO_2 Uniaxial Trigonal $P3_12$; $P3_22$
Optical properties	Transparency (visible) Colour Birefringence Refractive index @ 590 nm Band gap eV	YES Colourless YES o – 1.544 e – 1.553 8.4
Physical properties	Density g/cm^3 Moh's hardness	2.649 7

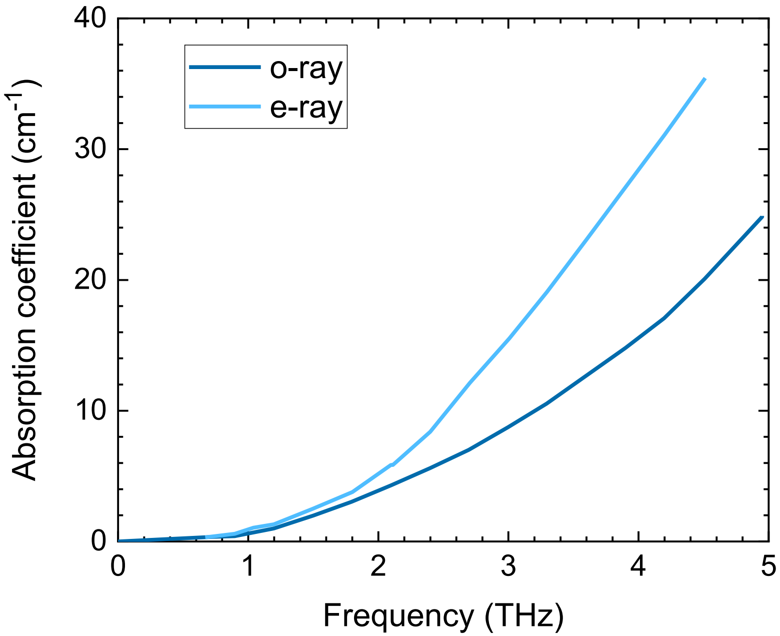


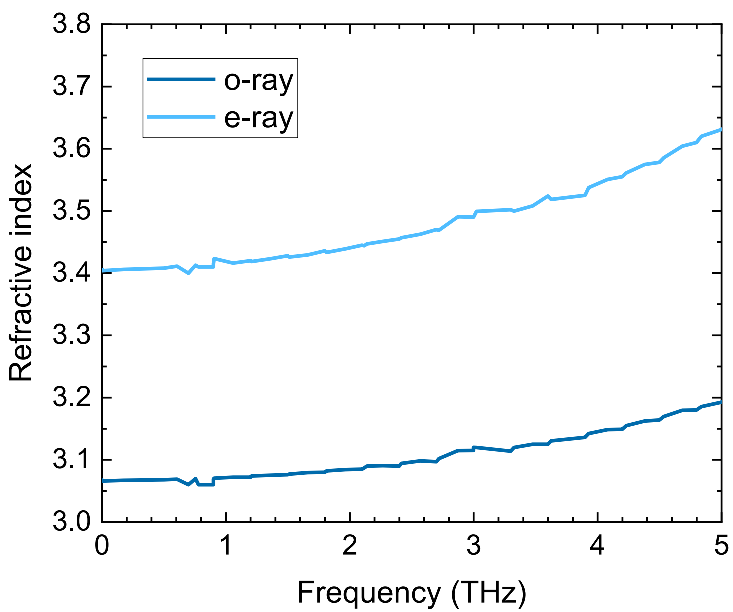


Sapphire Al_2O_3



Crystal properties	Chemical formula Crystal type Crystal system	Al_2O_3 Uniaxial Trigonal R3c
Optical properties	Transparency (visible) Colour Birefringence Refractive index @ 590 nm Band gap eV	YES Colourless YES o – 1.7680 e – 1.7600 9.9
Physical properties	Density g/cm^3 Moh's hardness	3.97 9





THz-transparent crystals

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Crystal	THz refractive index	Absorption @ 1 THz (cm^{-1})	Absorption @ 3 THz (cm^{-1})	Absorption @ 10 THz (cm^{-1})	Transparency in the visible
Diamond	2.38	0.1	0.12	0.27	Yes
Silicon	3.42	0.1	0.1	0.3	No
Germanium	4.01	0.2	1.3	20	No
Silicon carbide (4H-SiC)	3.13	0.1	0.4	6	Yes
Z- cut Quartz	2.11	0.2	1.2	45	Yes
Z- cut Sapphire	3.1	1.0	9	68	Yes

Non-polar polymers

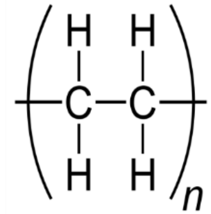
National Physical Laboratory

How to recognise non-polar polymers?

Polymers containing only C and H (or F) atoms

Polyethylene

Appearance: milky-white



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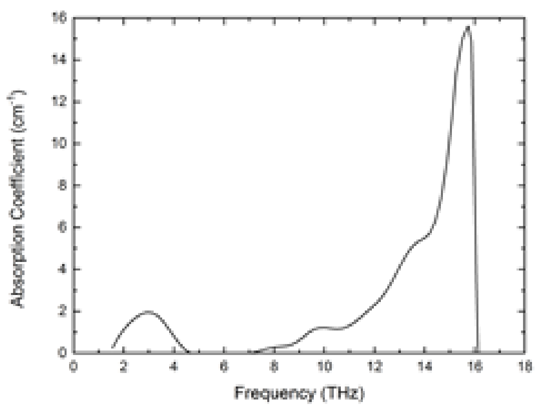
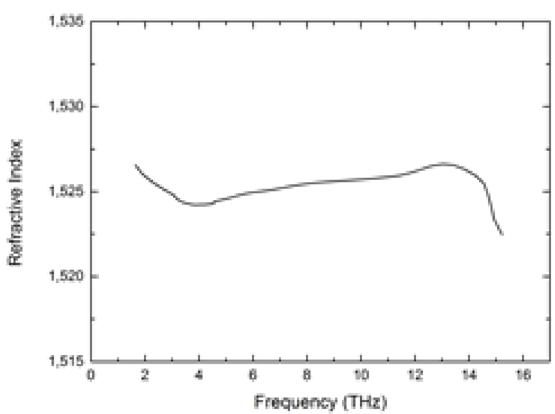
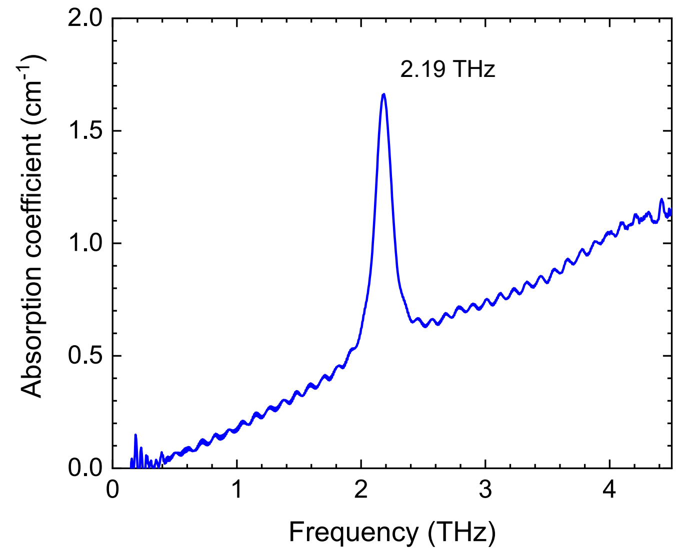
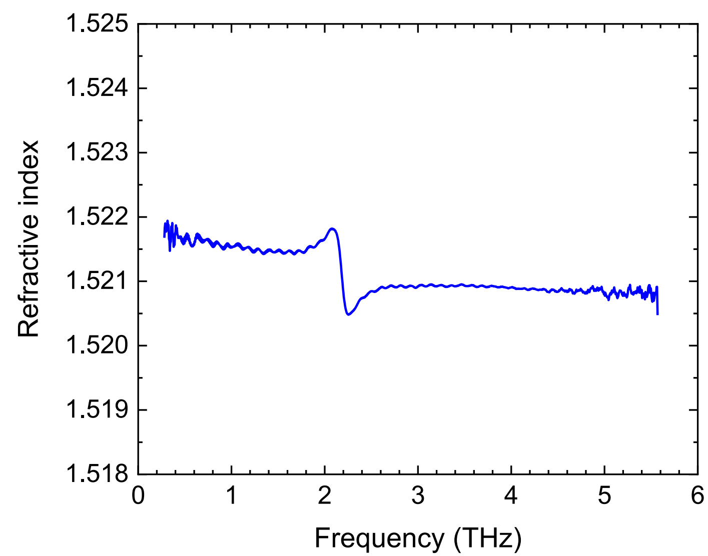
High density polyethylene (HDPE)
Low density polyethylene (LDPE)
Linear low density polyethylene (LLDPE)
High molecular weight polyethylene (HMWPE)
Ultra high molecular weight polyethylene (UHMWPE)



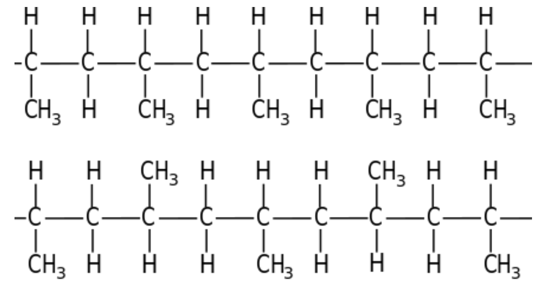


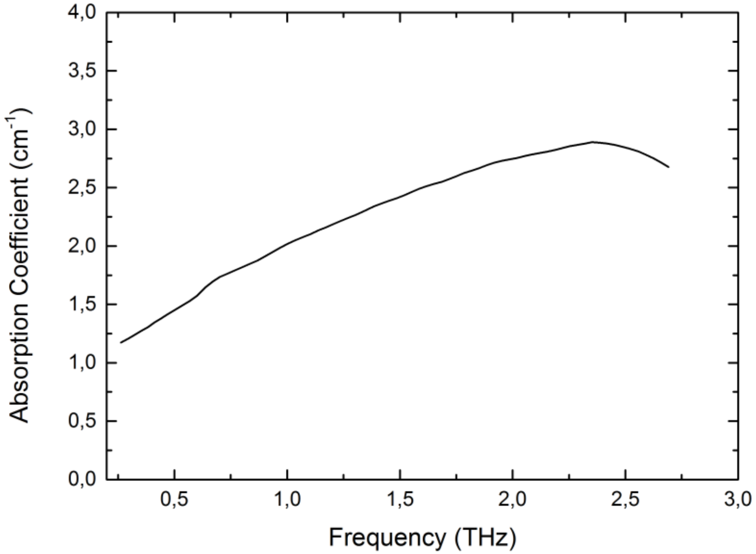


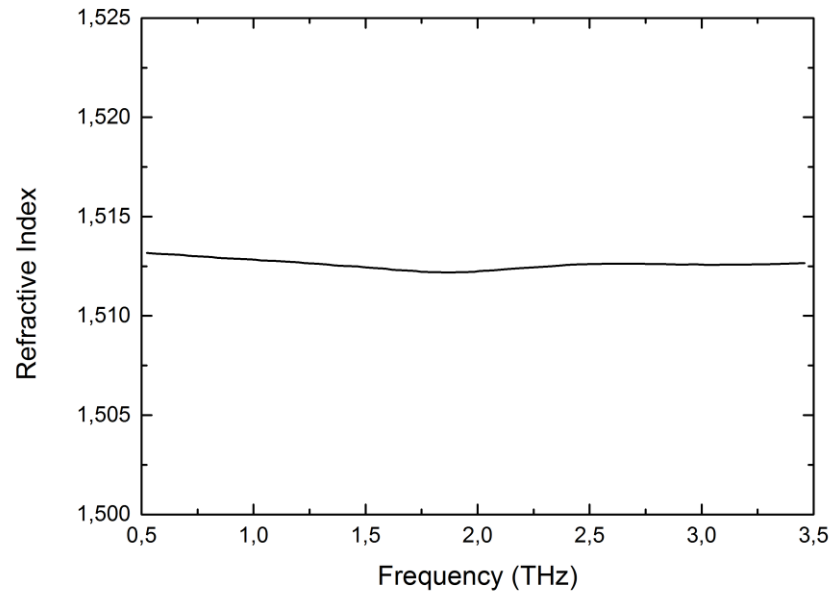


Polypropylene

Appearance: colourless & transparent







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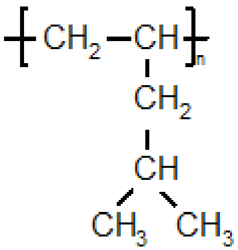
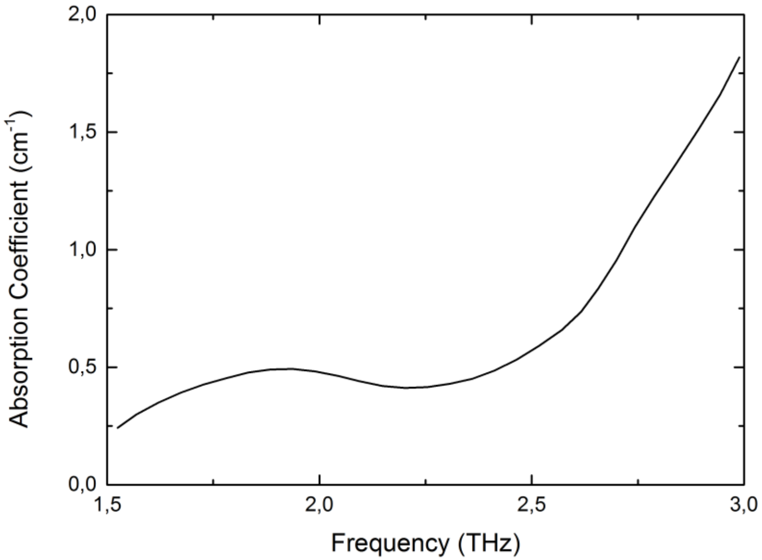
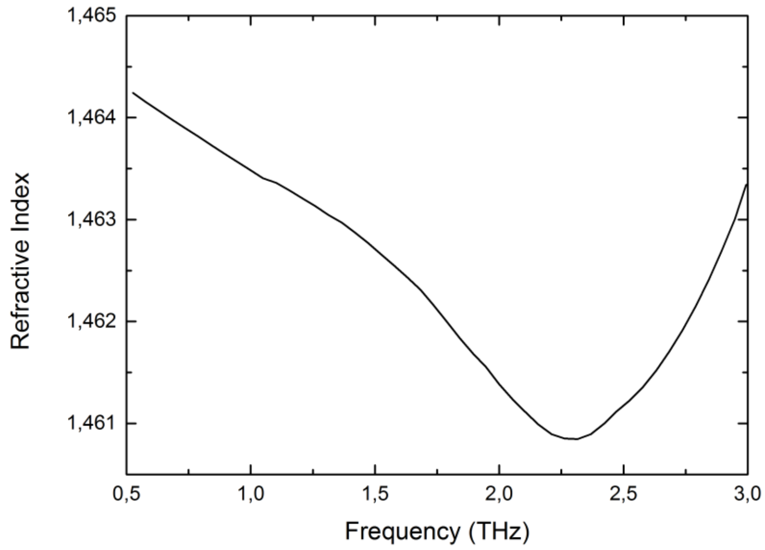
Poly-methyl-pentene PMP (TPX)

Appearance: colourless & transparent

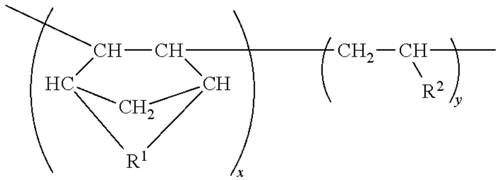


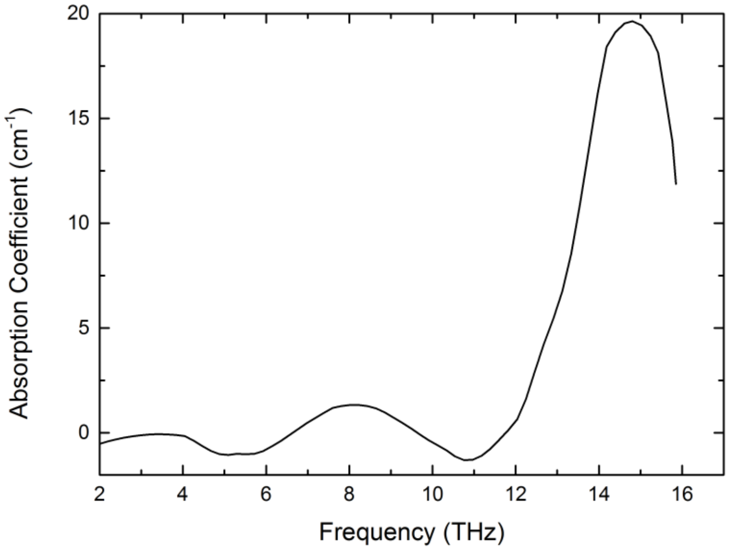


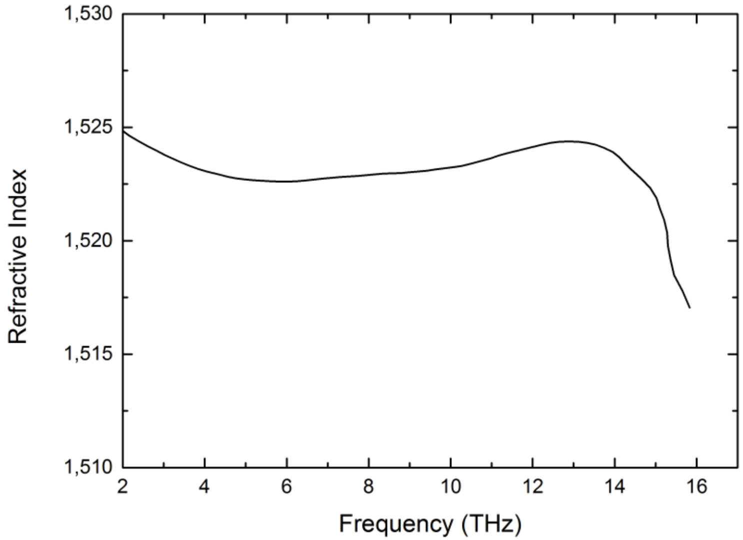


Cyclo-olefin copolymer COC

Appearance: colourless & transparent

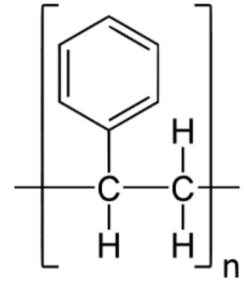






Polystyrene

Appearance: colourless & transparent



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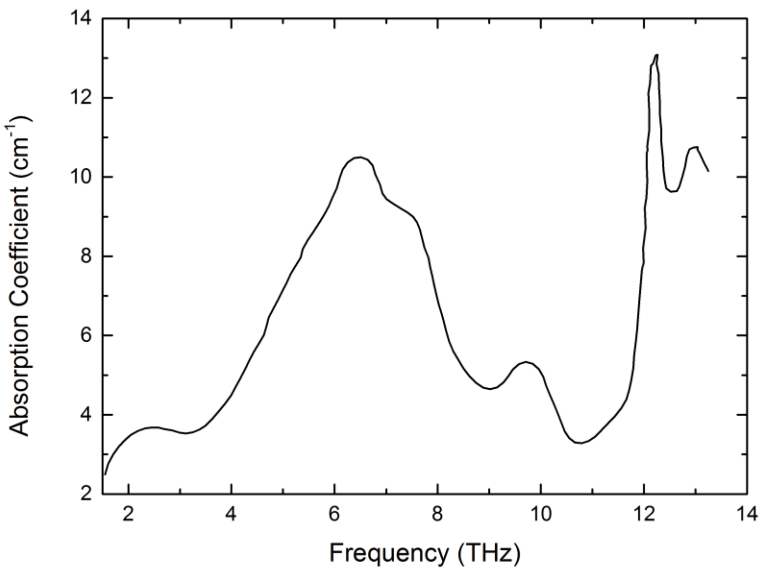
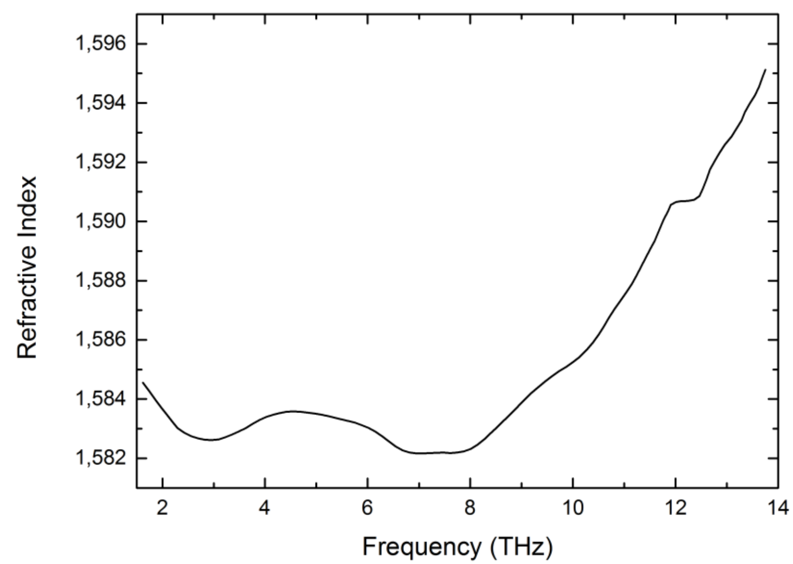
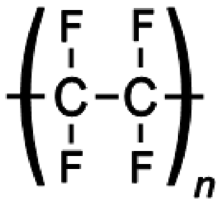
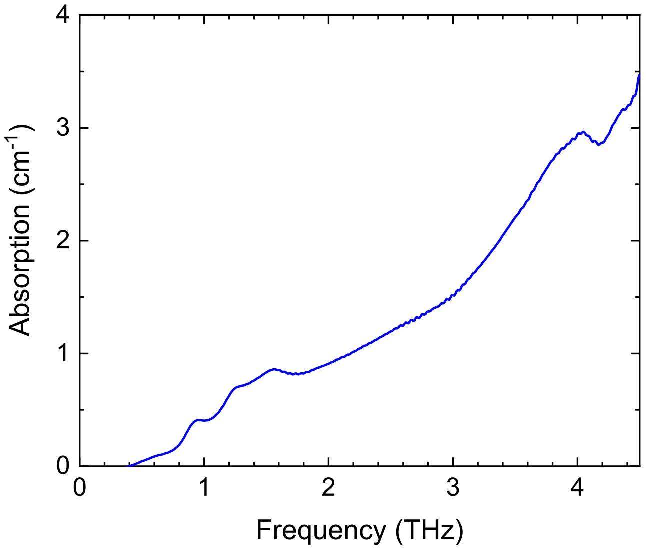


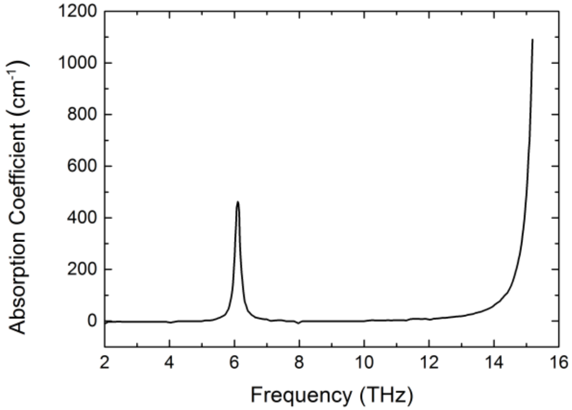


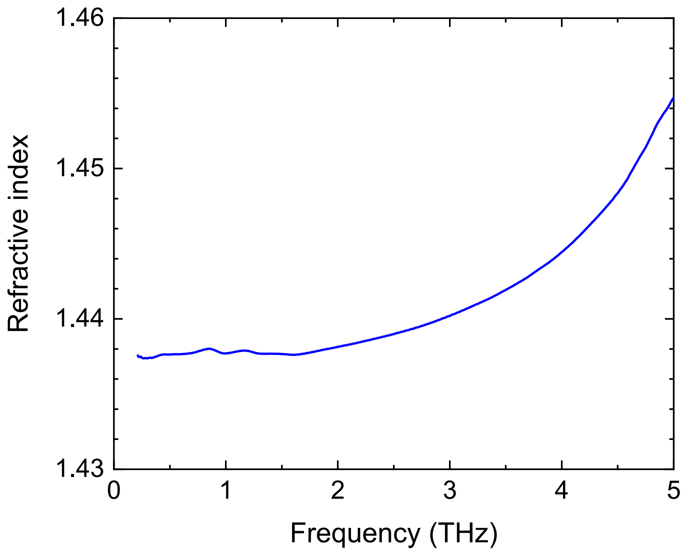
Polytetrafluoroethylene PTFE (Teflon)

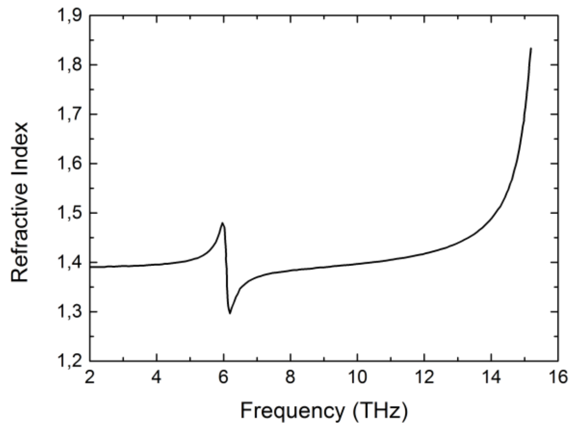
Appearance: bright white



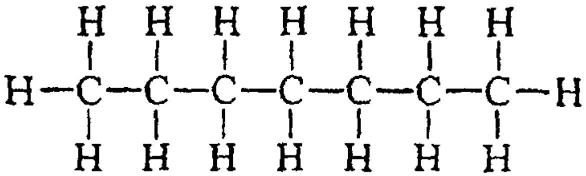








Paraffin wax, jelly and liquid

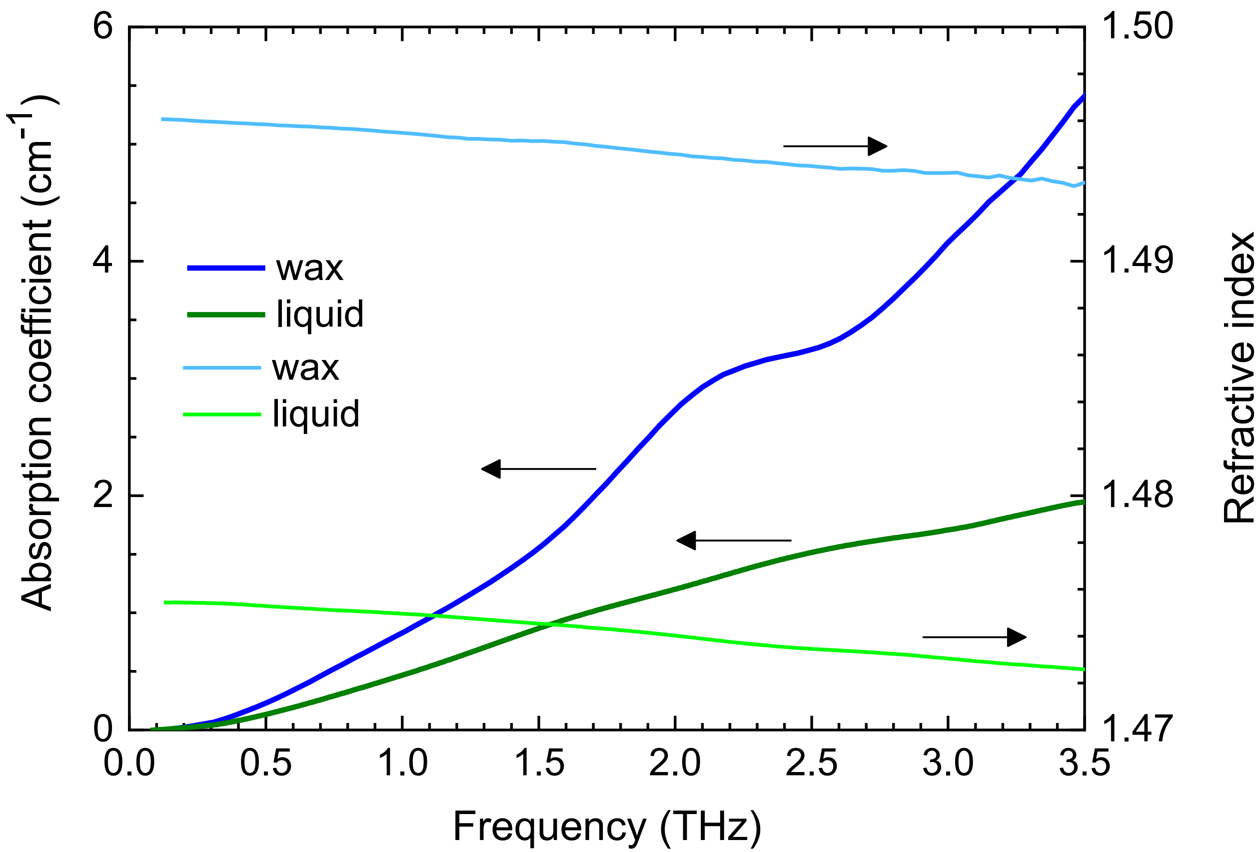


- Alkanes whose formula is C_2H_{2n+2} .
- Wax has chains of 20-40 atoms;
  liquid has chains of 6-16 atoms;
  jelly is a mixture of longer and shorter chains.

- Wax and jelly are both partially crystalline, and appear translucent.
- Liquid paraffin is colourless and transparent.

► Paraffins can be used as mounting or suspension media for a wide variety of materials and powders, and as optical contact media.

Paraffin



6
4
2
0
1.50
1.49
1.48
1.47
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Absorption coefficient (cm⁻¹)
Refractive index
Frequency (THz)
wax
liquid
wax
liquid

THz-transparent polymers

National Physical Laboratory

Polymer	THz refractive index (mean)	Absorption @ 1 THz (cm^{-1})	Absorption @ 3 THz (cm^{-1})	Absorption @ 10 THz (cm^{-1})	Transparency in the visible
LDPE	1.51	0.2	1.6	~2	No
HDPE	1.53	0.2	1.6	~3	No
PTFE	1.43	0.5	2.8	>50	No
COC	1.52-1.53	0.2	0.8	~2	Yes
PMP (TPX)	1.46	0.3	0.8	~2.5	Yes
PP	1.52	0.3	~1.5	~3.5	Yes
PS	1.58	1.5	2.5	~5	Yes
Paraffin liq.	1.47	0.5	1.7	NA	Yes
Paraffin wax	1.49	0.8	4.2	NA	No

Note: Polymers that are transparent in the visible and at THz have similar refractive indices in both regions ($\boldsymbol{n}_{\mathbf{visible}} \cong \boldsymbol{n}_{\mathbf{THz}}$).
This aids THz beam path alignment using visible light.

Thank you

Millimetre-wave characterisation of dielectric materials using a guided free-space technique

Dr Xiaobang Shang, Prof Nick Ridler

National Physical Laboratory, UK

Xiaobang.Shang@npl.co.uk, Nick.Ridler@npl.co.uk

1st TEMMT Training Course, 21-July-2021

Outline

- Introduction
- Material Characterisation Kit (MCK)
  - Assessment at WR-15 band
  - New calibration methods
  - Data filtering techniques
- Conclusions

Introduction – Permittivity and Permeability

Permittivity

$$\frac{\varepsilon}{\varepsilon_0} = \varepsilon_r = \varepsilon_r' - j\varepsilon_r''$$

interaction of a material in the presence of an external electric field.

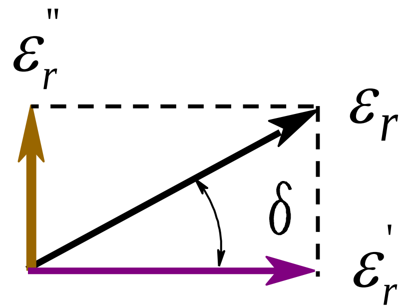
Permeability

$$\frac{\mu}{\mu_0} = \mu_r = \mu_r' - j\mu_r''$$

interaction of a material in the presence of an external magnetic field.

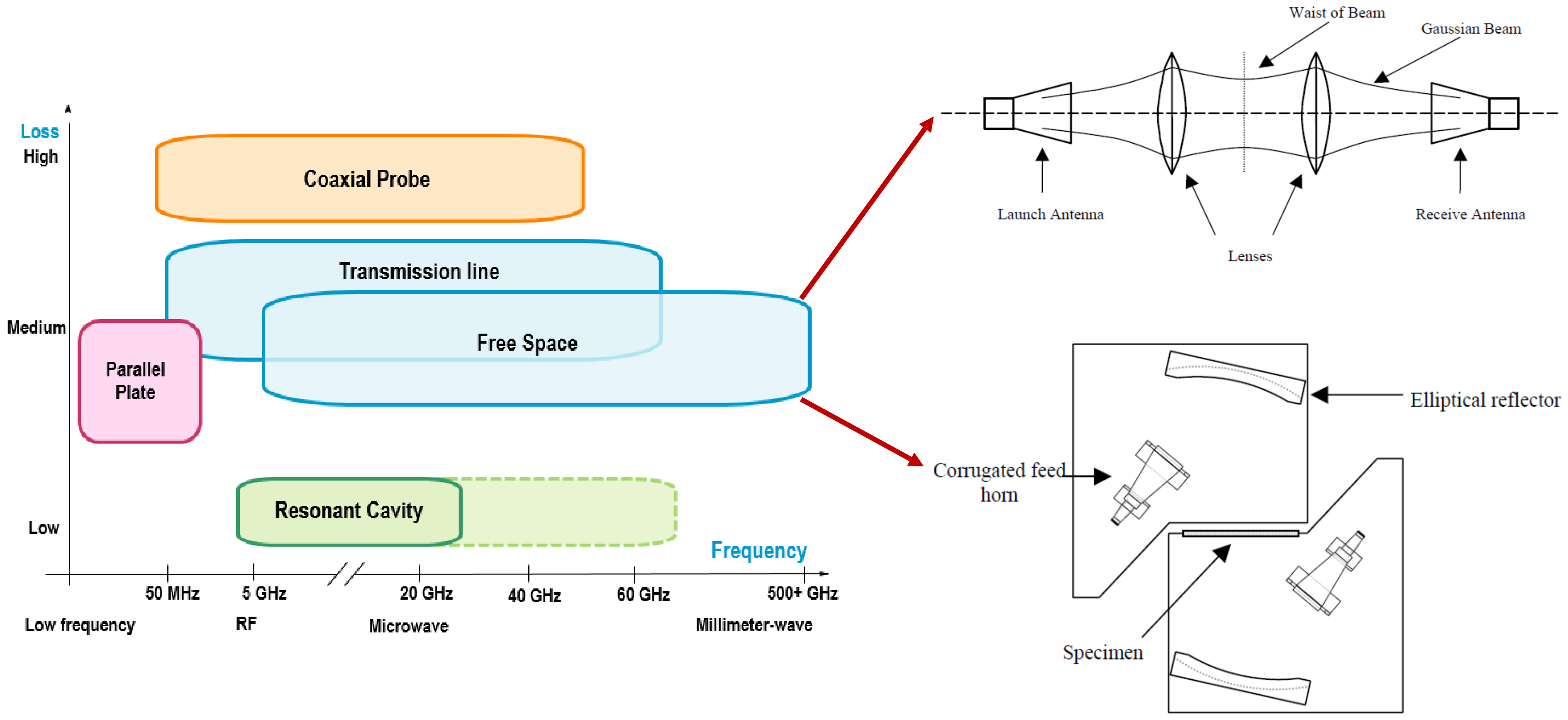
Loss tangent

$$\tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'}$$



[Shelley Begley: "Electromagnetic properties of materials"]

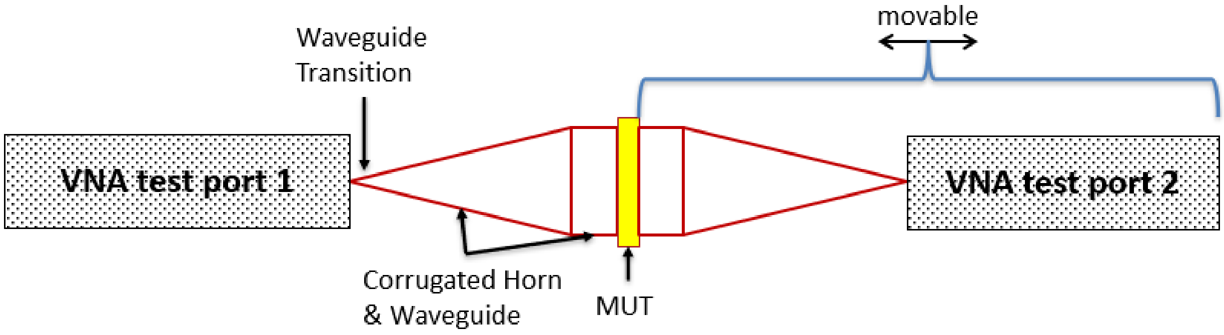
Introduction – Typical Measurement Methods

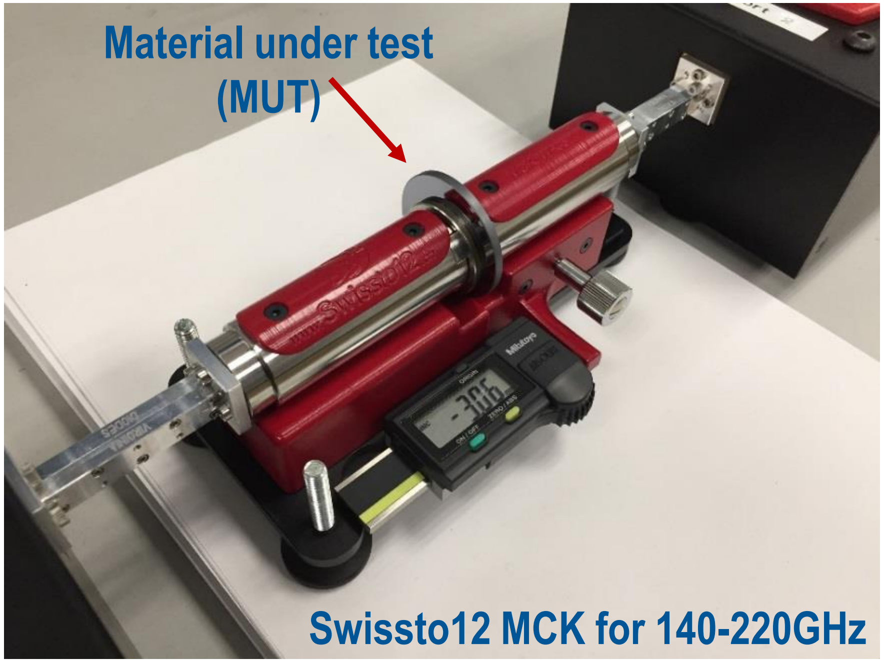


- TDS (Time-Domain Spectrometry) is another popular technique utilised for characterising material properties at THz frequencies

[Shelley Begley: "Electromagnetic properties of materials" & R N Clarke *et al*: "A guide to the characterisation of dielectric materials at RF and microwave frequencies"]

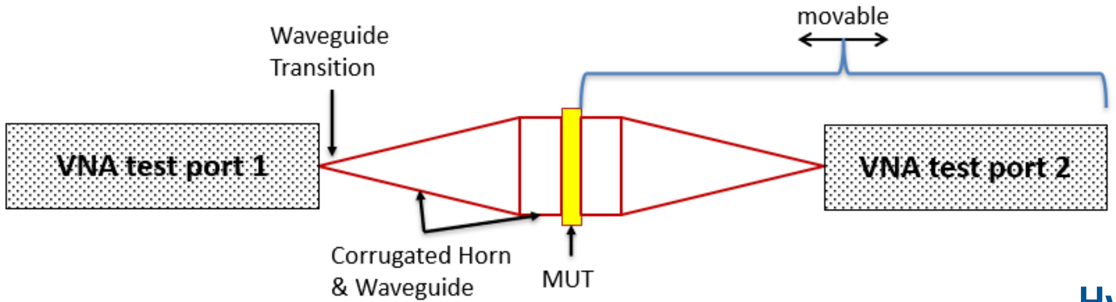
Material Characterisation Kit (MCK)

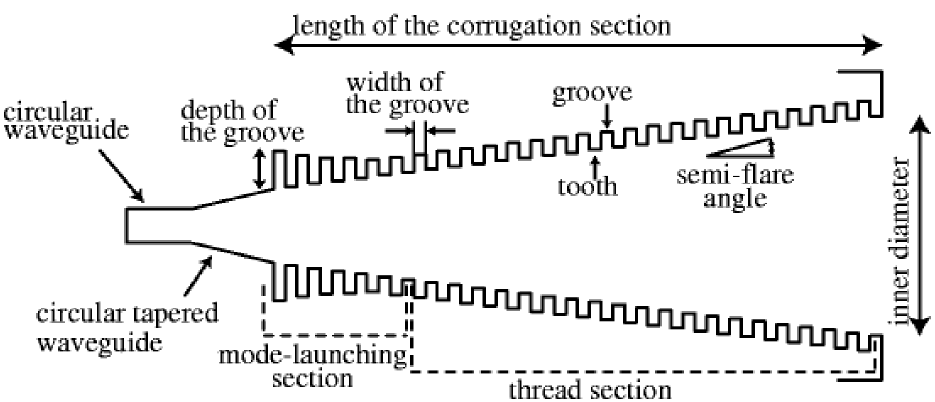


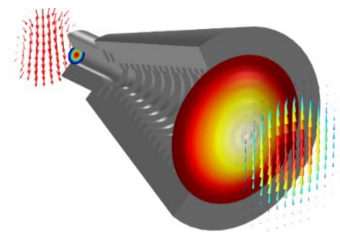


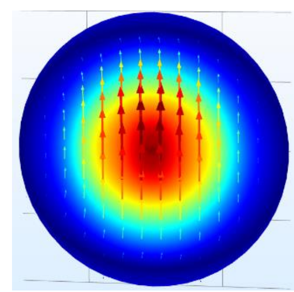
[A Dimitriadis *et al*: "Dielectric measurements at mm-wave frequencies with the material characterization kit (MCK)"]

Material Characterisation Kit (MCK)

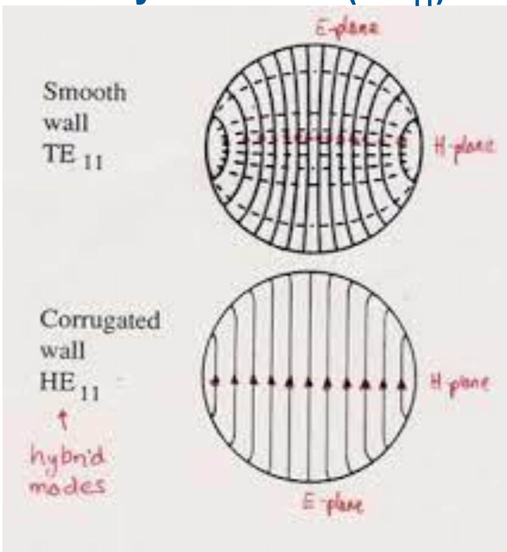








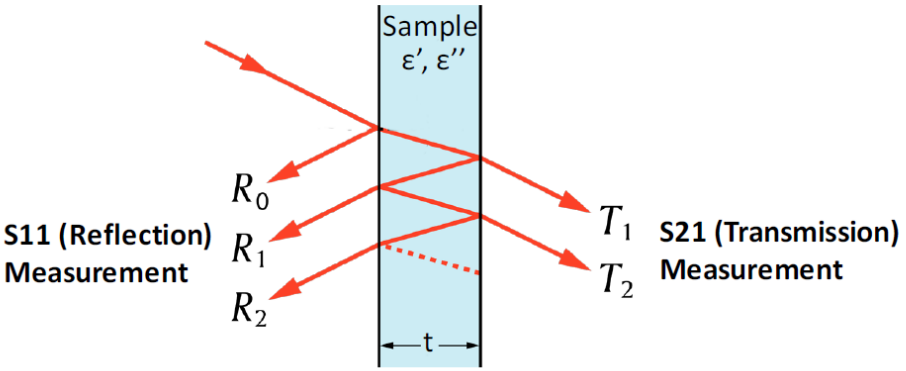
Hybrid mode (HE_{11})

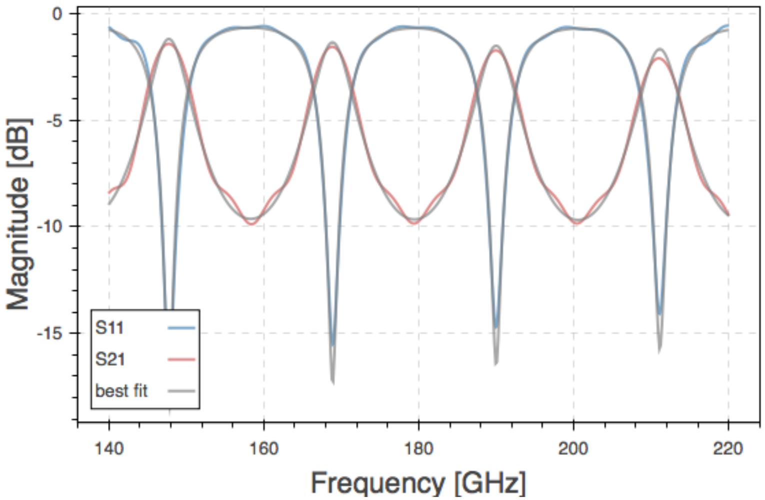


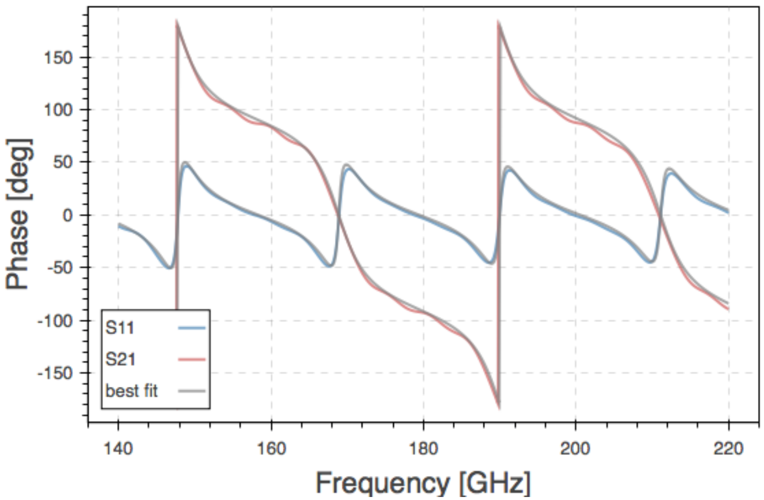
- Effectively a *guided free-space* technique: MCKs are more compact and have less stringent requirement on alignment, compared to conventional free-space systems
- HE_{11} hybrid mode (linear polarization): mode purity >98%

[A Dimitriadis *et al*: “Dielectric measurements at mm-wave frequencies with the material characterization kit (MCK)”]

Material Characterisation Kit (MCK)







$YZrO_2$ (1.23 mm thickness)

[A Dimitriadis *et al*: “Dielectric measurements at mm-wave frequencies with the material characterization kit (MCK)”]

Research into MCKs

- NPL currently has 4 sets of MCKs, covering 50-75GHz, 75-110GHz, 140-220GHz, 500-750GHz
- Research focus:
  - Measurement uncertainties
  - Enhanced calibration techniques, e.g. TRL
  - Algorithms for extraction of complex permittivity from S-parameters

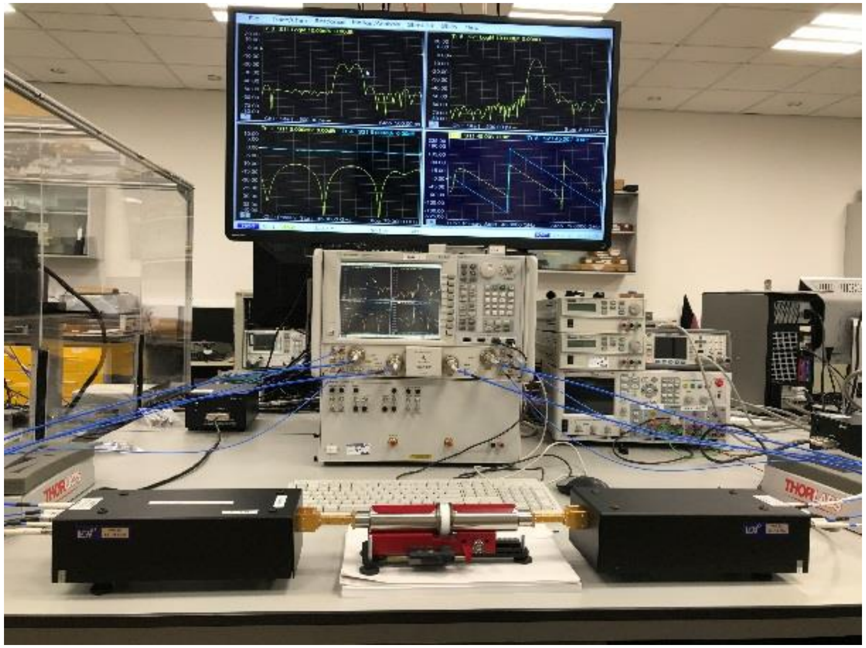
    …..

Time Gating

Calibration techniques recommended by manufacturer

Next, we will review 3 pieces of work undertaken by NPL

MCK 1: Investigation at WR-15 (50-75GHz)

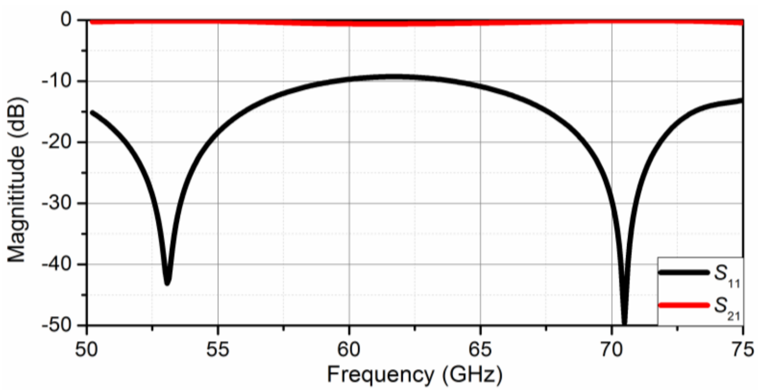


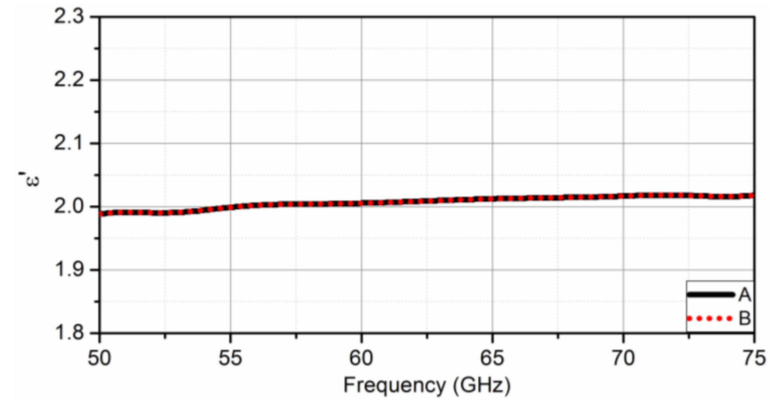
- *S*-parameters measured on PNA-X with VDI frequency extender heads
- Permittivity extracted from *S*-parameters using NIST precision model (only S_{21} used)
- Free-space calibration based on Short/Thru, together with time-gating. No need for prior waveguide calibration

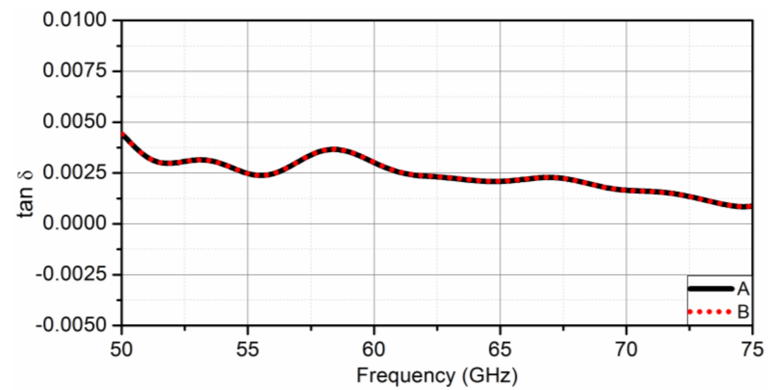
Y. Wang, X. Shang, N. M. Ridler, T. Huang and W. Wu, "Characterization of Dielectric Materials at WR-15 Band (50–75 GHz) Using VNA-Based Technique," in IEEE Transactions on Instrumentation and Measurement, vol. 69, no. 7, pp. 4930-4939, July 2020

MCK 1: Investigation at WR-15 (50-75GHz)

Results of 6mm thick PTFE







- Similar measurements performed for materials: Astra MT77, Rogers 3003, TPX, HDPE, Alumina, Silicon

Y. Wang, X. Shang, N. M. Ridler, T. Huang and W. Wu, "Characterization of Dielectric Materials at WR-15 Band (50–75 GHz) Using VNA-Based Technique," in IEEE Transactions on Instrumentation and Measurement, vol. 69, no. 7, pp. 4930-4939, July 2020

MCK 1: Investigation at WR-15 (50-75GHz)

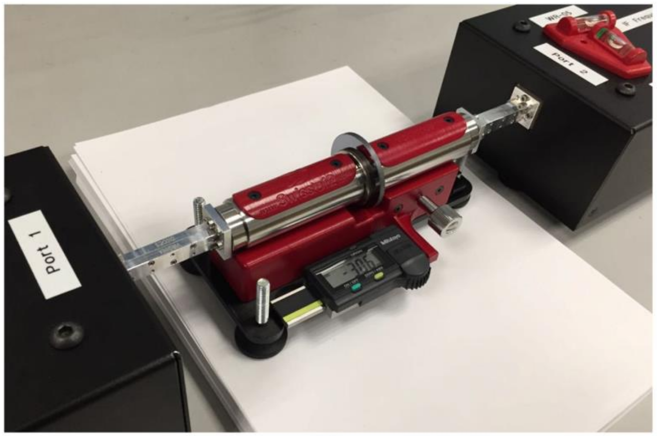
- Good agreement between measured results using MCK & published values in literature
- Preliminary estimates of the uncertainty obtained – see the paper for details. Generally, systematic errors dominate the overall uncertainty, i.e. accuracy of S-parameters and sample thickness important

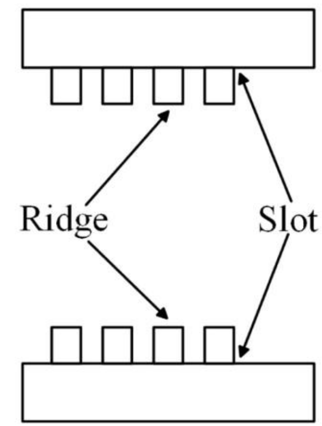
Sample	Thickness (mm)	ε' (extracted)	ε' (literature)
PTFE	5.99	2.008	2.1 @ 12 GHz, [25] 2.06 @ 92.5 GHz, [26]
Astra MT77	1.60	2.988	3.0 @ 79 GHz, [19] 3.0 @ 10 GHz, [27]
Rogers 3003	1.50	3.110	3.0 @ 60 GHz, [20] 3 @ 10 GHz, [28]
TPX	2.81	2.099	2.13 @ 38 GHz, [29] 2.136 @ 700 GHz, [30]
HDPE	5.97	2.301	2.3 @ 700 GHz, [30] 2.2505 @ 85 GHz, [31]
Alumina	10.18	9.618	9.4 @ 2.5 THz, [33] 9.424 @ 17 GHz, [32]
Silicon	3.06	11.678	11.7 @ 700 GHz, [30] 11.67 @ 1 THz, [33]

Sample	Thickness (mm)	tan δ (extracted)	tan δ (literature)
PTFE	5.99	0.002	0.000 3 @ 12 GHz, [25] 0.000 389 @ 92.5 GHz, [26]
Astra MT77	1.60	0.004	0.001 7 @ 79 GHz, [19] 0.001 7 @ 10 GHz, [27]
Rogers 3003	1.50	0.001	0.001 3 @ 60 GHz, [20] 0.001 3 @ 10 GHz, [28]
TPX	2.81	0.003	0.004 3 @ 38 GHz, [29] 0.001 74 @ 700 GHz, [30]
HDPE	5.97	0.002	0.000 224 @ 700 GHz, [30] 0.000 225 217 @85 GHz, [31]
Alumina	10.18	0.001	0.021 @ 2.5 THz, [33] 0.000 31 @ 17 GHz, [32]
Silicon	3.06	0.001	0.000 26 @ 700 GHz, [30] 0.000 4 @ 1 THz, [33]

Y. Wang, X. Shang, N. M. Ridler, T. Huang and W. Wu, "Characterization of Dielectric Materials at WR-15 Band (50–75 GHz) Using VNA-Based Technique," in IEEE Transactions on Instrumentation and Measurement, vol. 69, no. 7, pp. 4930-4939, July 2020

MCK 2: TRL Calibration

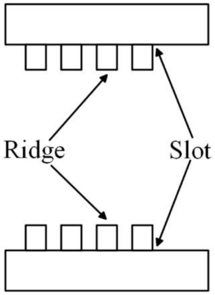




- Thru-Reflect-Line (TRL) calibration applied to MCK, to obtain robust S-parameters for calculation of permittivity and loss tangent
- Investigation undertaken at WR-5 (140-220GHz) and WM-380 (500-750GHz)
- TDS was used for benchmarking
- TRL calibration offers improvement in results

Y. Wang *et al.*, "Material Measurements Using VNA-Based Material Characterization Kits Subject to Thru-Reflect-Line Calibration," in IEEE Transactions on Terahertz Science and Technology, vol. 10, no. 5, pp. 466-473, Sept. 2020

MCK 2: TRL Calibration



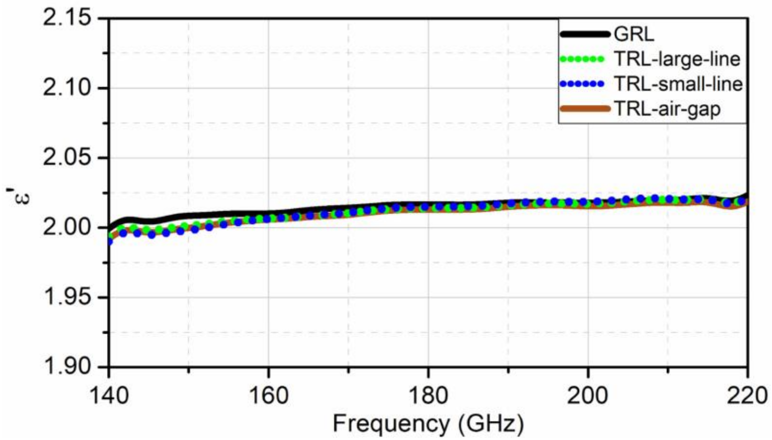
	WR-5	WM-380
Mid-band frequency (GHz)	180	625
Ridge diameter (mm)	8.200	5.000
Slot diameter (mm)	9.052	5.250
λ/4 corrugated waveguide (mm)	0.422	0.120
λ/4 free-space (mm)	0.416	0.120
Air gap length used (mm)	0.420	0.120

- Line standard can be either a metal waveguide or air gap, both work effectively
- Air gap is desirable as no additional standard required
- Time-gating was still applied, and the optimum gate width varies with samples and can be calculated

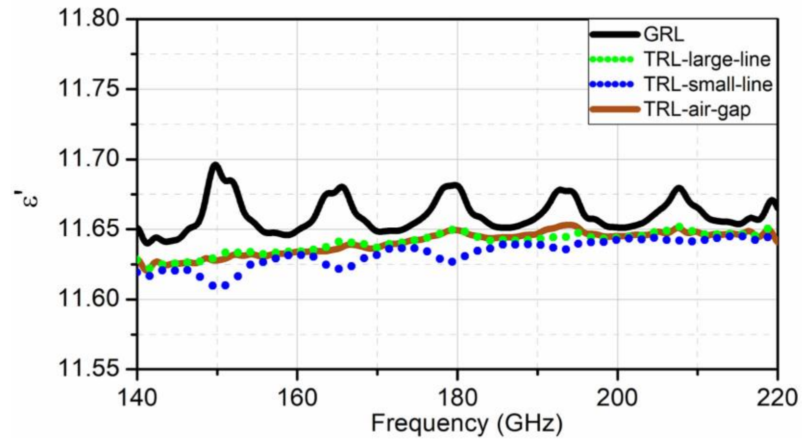
- TRL shows improvement in results for some difficult samples with relatively large dielectric constants. Good agreement between MCK (with TRL) and TDS results. *See next 2 slides*

Y. Wang *et al*., "Material Measurements Using VNA-Based Material Characterization Kits Subject to Thru-Reflect-Line Calibration," in IEEE Transactions on Terahertz Science and Technology, vol. 10, no. 5, pp. 466-473, Sept. 2020

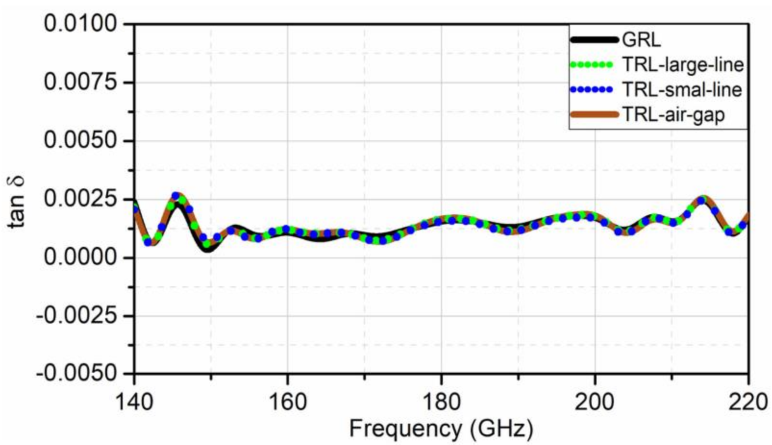
MCK 2: TRL Calibration



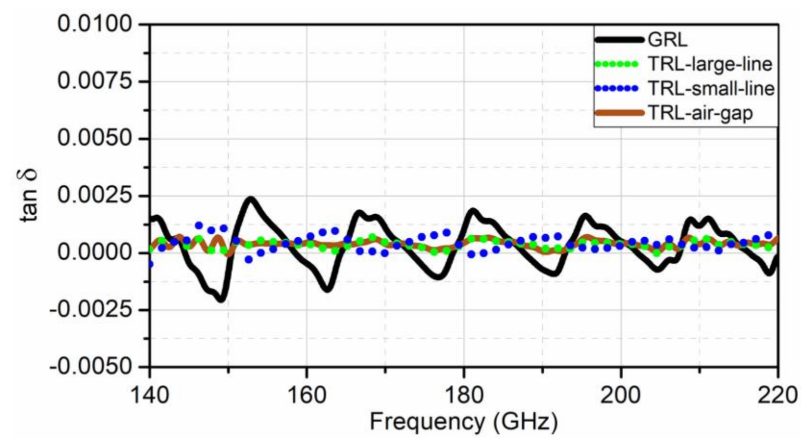
(a)



(a)



(b)



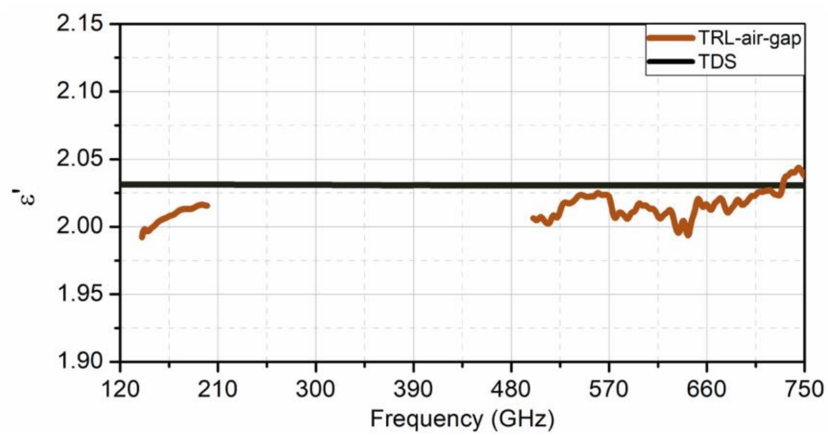
(b)

PTFE (6 mm thickness)

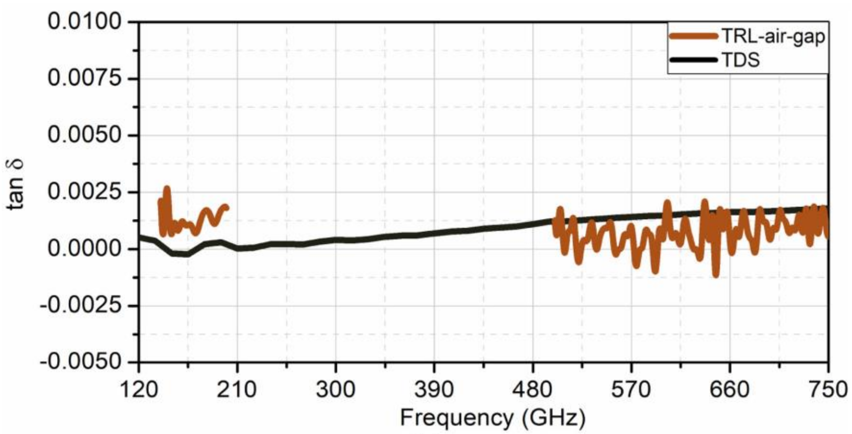
Silicon (2 mm thickness)

Y. Wang *et al*., "Material Measurements Using VNA-Based Material Characterization Kits Subject to Thru-Reflect-Line Calibration," in IEEE Transactions on Terahertz Science and Technology, vol. 10, no. 5, pp. 466-473, Sept. 2020

MCK 2: TRL Calibration

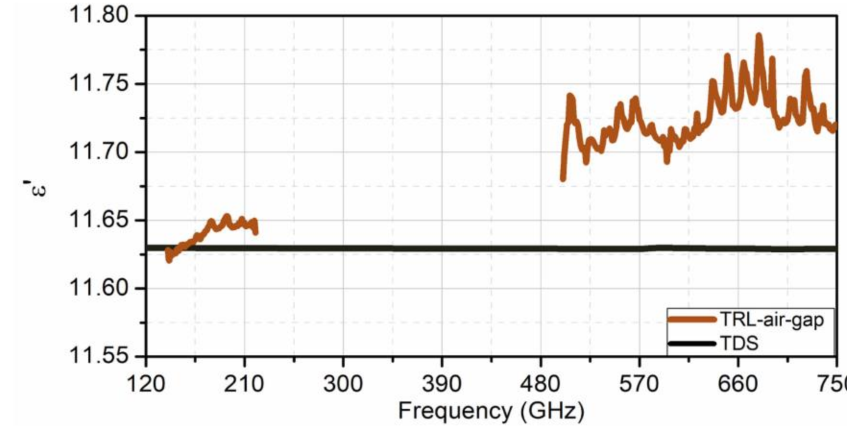


(a)

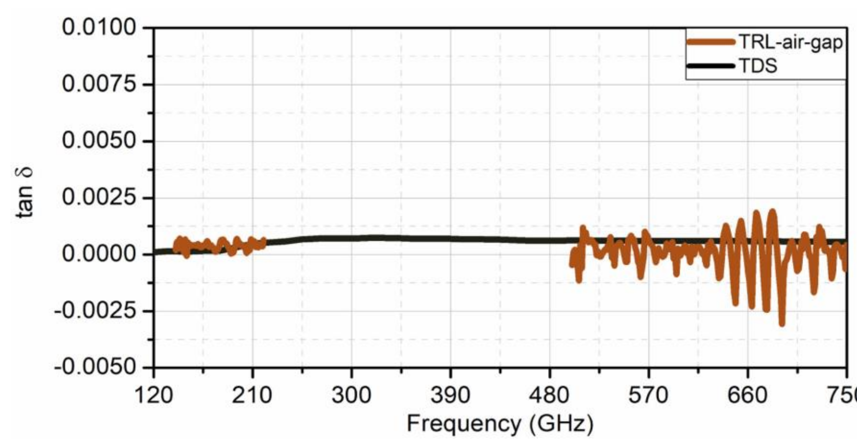


(b)

PTFE (6 mm thickness)



(a)

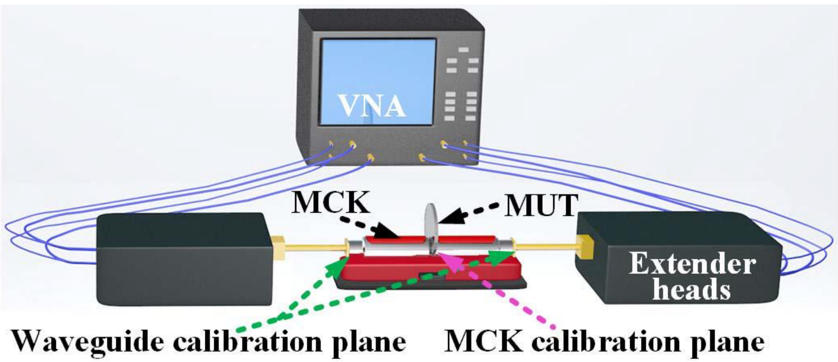


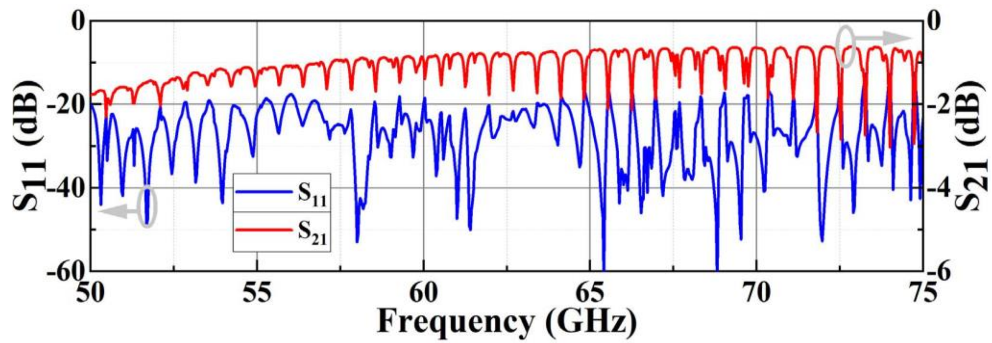
(b)

Silicon (2 mm thickness)

Y. Wang *et al.*, "Material Measurements Using VNA-Based Material Characterization Kits Subject to Thru-Reflect-Line Calibration," in IEEE Transactions on Terahertz Science and Technology, vol. 10, no. 5, pp. 466-473, Sept. 2020

MCK 3: Data Filtering

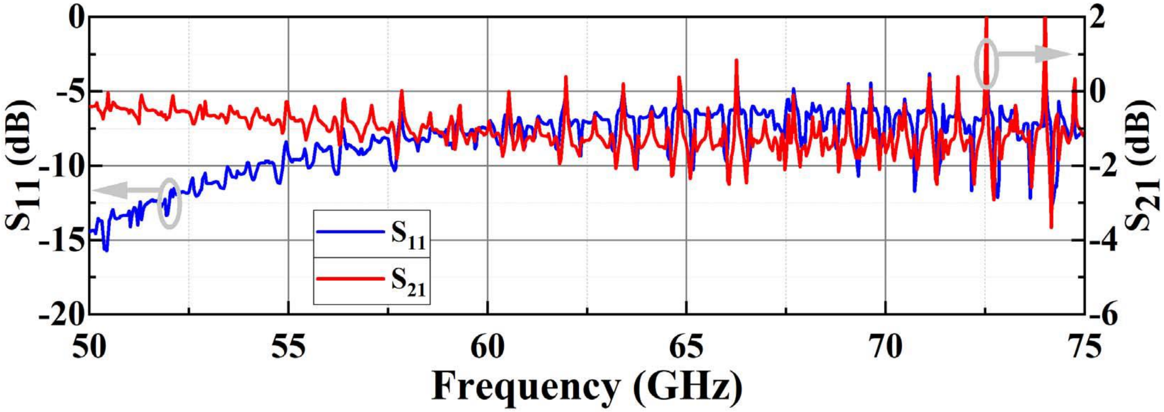




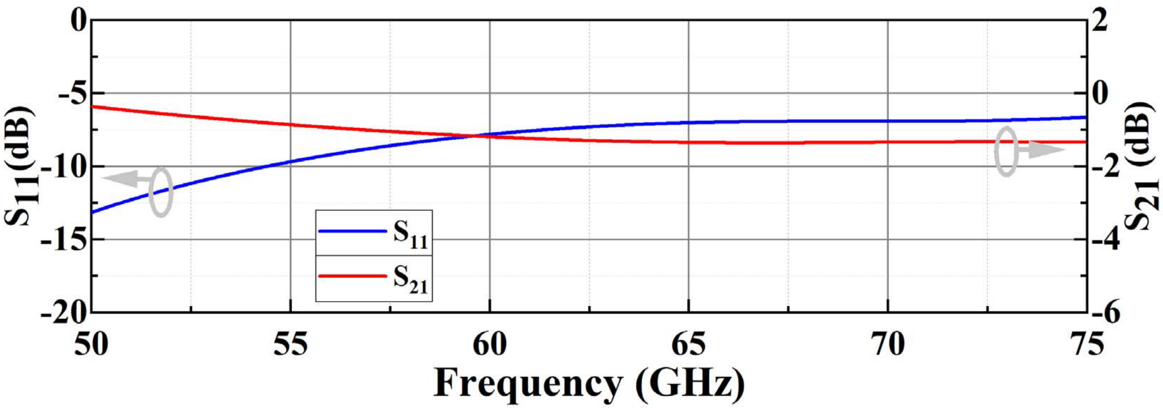
- Data filtering technique (i.e. Savitzky–Golay filter) was applied to measured S-parameters, eliminating the need for time-gating
- Generally Savitzky-Golary filter results are consist with time-gating results, and the former works better for specimens with non-ideal quality
- MCK results were compared with open-resonator data, showing good agreement

D. Ma, X. Shang, N. M. Ridler and W. Wu, "Assessing the Impact of Data Filtering Techniques on Material Characterization at Millimeter-Wave Frequencies," in IEEE Transactions on Instrumentation and Measurement, vol. 70, pp. 1-4, 2021, Art no. 6005904

MCK 3: Data Filtering



- Acetal co-polymer sample 2mm thickness
- Responses after MCK TRL calibration
- Time-gating was not applied

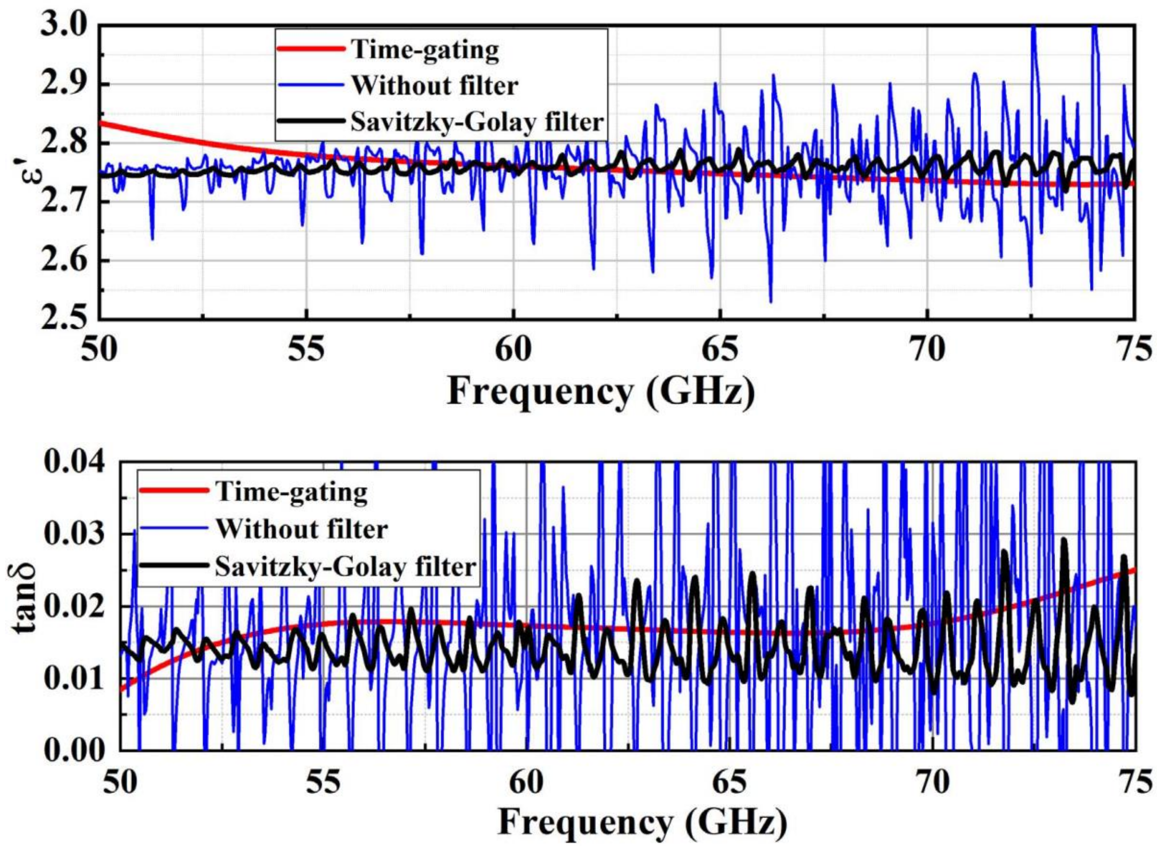


- Acetal co-polymer sample 2mm thickness
- Time-gating was applied

- Time-gating can effectively clean up the data

D. Ma, X. Shang, N. M. Ridler and W. Wu, "Assessing the Impact of Data Filtering Techniques on Material Characterization at Millimeter-Wave Frequencies," in IEEE Transactions on Instrumentation and Measurement, vol. 70, pp. 1-4, 2021, Art no. 6005904

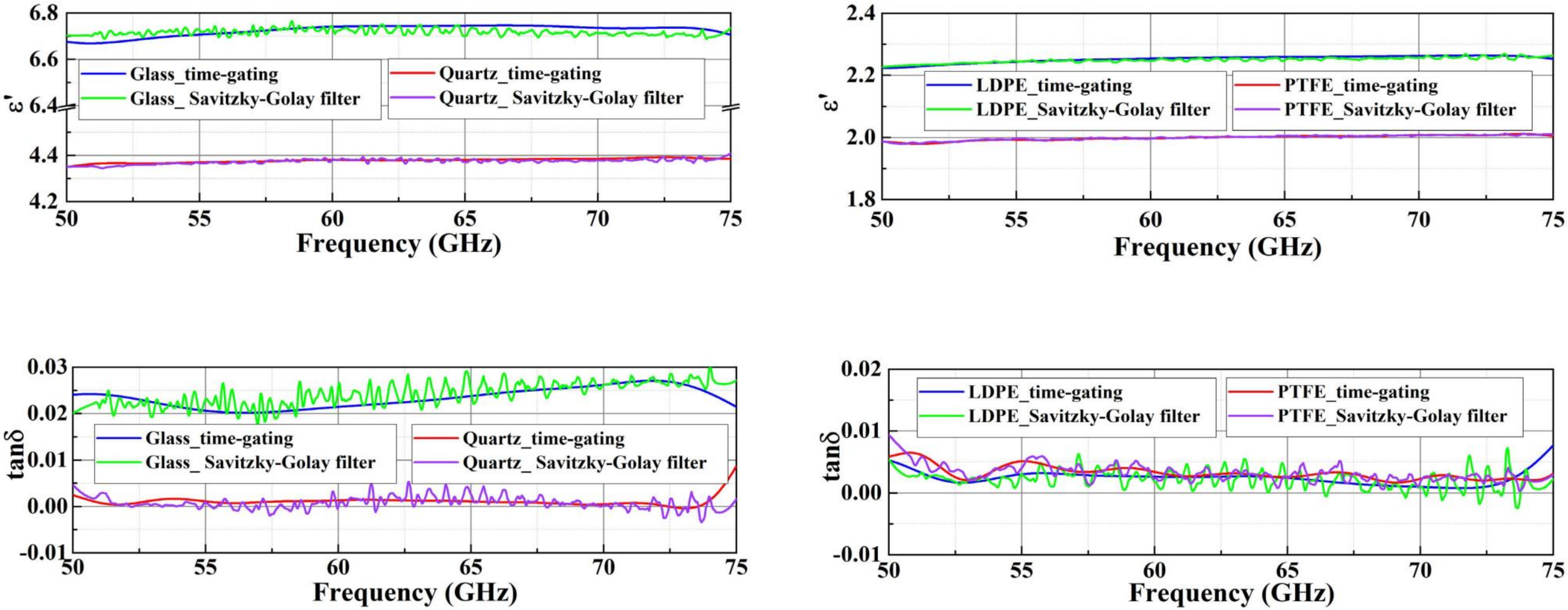
MCK 3: Data Filtering



- For the same acetal co-polymer sample, Savitzky-Golay filter works as effectively as time-gating

D. Ma, X. Shang, N. M. Ridler and W. Wu, "Assessing the Impact of Data Filtering Techniques on Material Characterization at Millimeter-Wave Frequencies," in IEEE Transactions on Instrumentation and Measurement, vol. 70, pp. 1-4, 2021, Art no. 6005904

MCK 3: Data Filtering



- Comparison carried out on glass sample (thickness 1.6mm), LDPE sample (thickness 6mm), quartz sample (thickness 4.1mm), and PTFE sample (thickness 12mm) too

D. Ma, X. Shang, N. M. Ridler and W. Wu, "Assessing the Impact of Data Filtering Techniques on Material Characterization at Millimeter-Wave Frequencies," in IEEE Transactions on Instrumentation and Measurement, vol. 70, pp. 1-4, 2021, Art no. 6005904

MCK 3: Data Filtering

TABLE I

COMPARISON OF ε' VALUES

Sample	MCK (Time-gating)	MCK (Savitzky-Golay filter)	Open-resonator
LDPE	2.253 ± 0.040	2.250 ± 0.038	2.286 ± 0.005
Glass	6.727 ± 0.059	6.718 ± 0.044	6.70 ± 0.04
Quartz	4.378 ± 0.037	4.374 ± 0.041	4.433 ± 0.013

TABLE II

COMPARISON OF $\tan\delta$ VALUES

Sample	MCK (Time-gating)	MCK (Savitzky-Golay filter)	Open-resonator
LDPE	0.002 ± 0.013	0.002 ± 0.013	0.00023 ± 0.00001
Glass	0.023 ± 0.014	0.024 ± 0.015	0.0221 ± 0.0012
Quartz	0.001 ± 0.012	0.0010 ± 0.013	0.000032 ± 0.000012

D. Ma, X. Shang, N. M. Ridler and W. Wu, "Assessing the Impact of Data Filtering Techniques on Material Characterization at Millimeter-Wave Frequencies," in IEEE Transactions on Instrumentation and Measurement, vol. 70, pp. 1-4, 2021, Art no. 6005904

Conclusions

- New guided free-space technique using Swissto12 MCKs was briefly described
- 3 pieces of recent work on assessing/improving MCK measurement method were summarised
- Other research work related to MCK, e.g. on extraction algorithms and new calibration methods, was also undertaken. See TEMMT project website – publication section
- Overall, MCK is a promising new technique enabling fast and easy material characterisations.

Acknowledgement

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EMPIR EURAMET

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