Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

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Electromagnetics Science Leader
National Physical Laboratory, UK

CCEM workshop “Future challenges in electrical metrology”, BIPM, Paris, 23 March 2017

Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

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Focus on three 'new' measurement topics . . .

I. **Filling the gap between microwaves and photonics**

II. **Multi-physics – more than just microwaves**

III. **When digital becomes analogue**

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III. When digital becomes analogue

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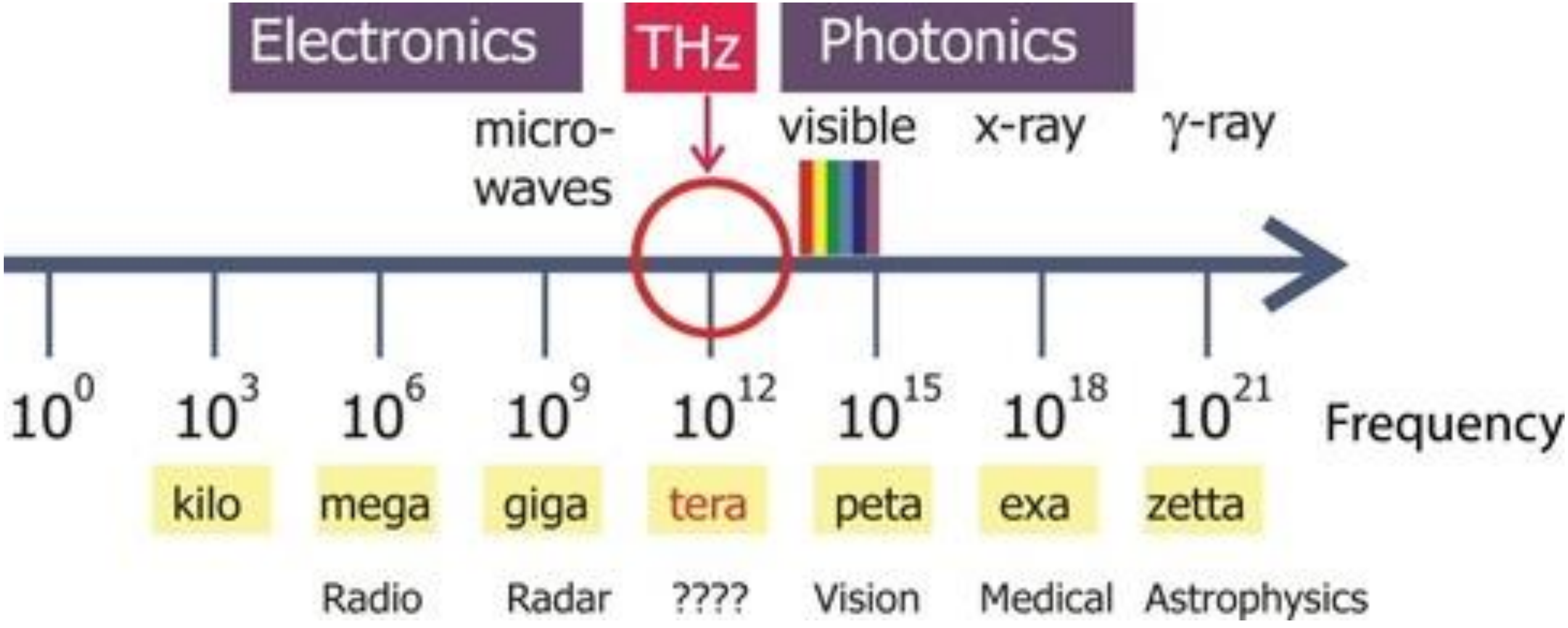
Filling the gap between electronics and photonics

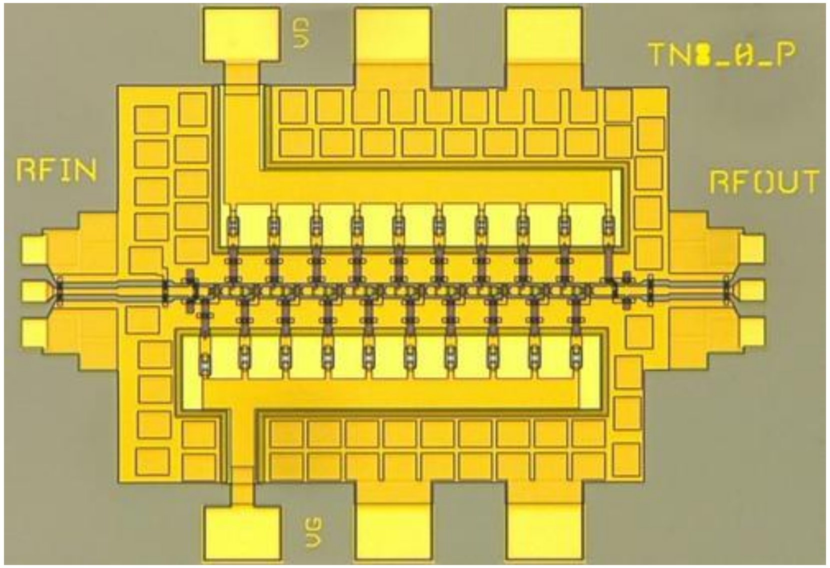


Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

Many applications

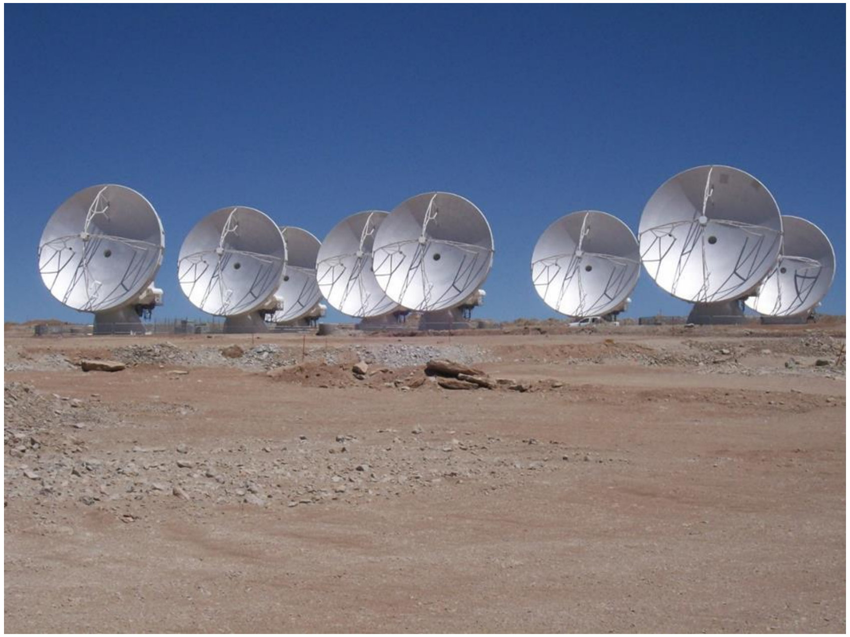
THz electronics

Terahertz Monolithic Integrated Circuit (TMIC)
InP amplifier (Northrop Grumman)



Radio Astronomy

ALMA – Atacama Large Millimeter/submillimeter Array
Location: Atacama dessert, Northern Chile
Telescope bandwidth: >950 GHz



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Many applications

Security

Airports and stand-off detection
Detecting weapons and other terrorist threats

Space

European Space Agency (ESA)
ISMAR - International Sub-Millimetre Airborne Radiometer Instrument
Observing precipitation and ice clouds (for climate change)

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New measurements . . . going from GHz to THz

- **Instrumentation – waveguides**
- **Devices – on-wafer**

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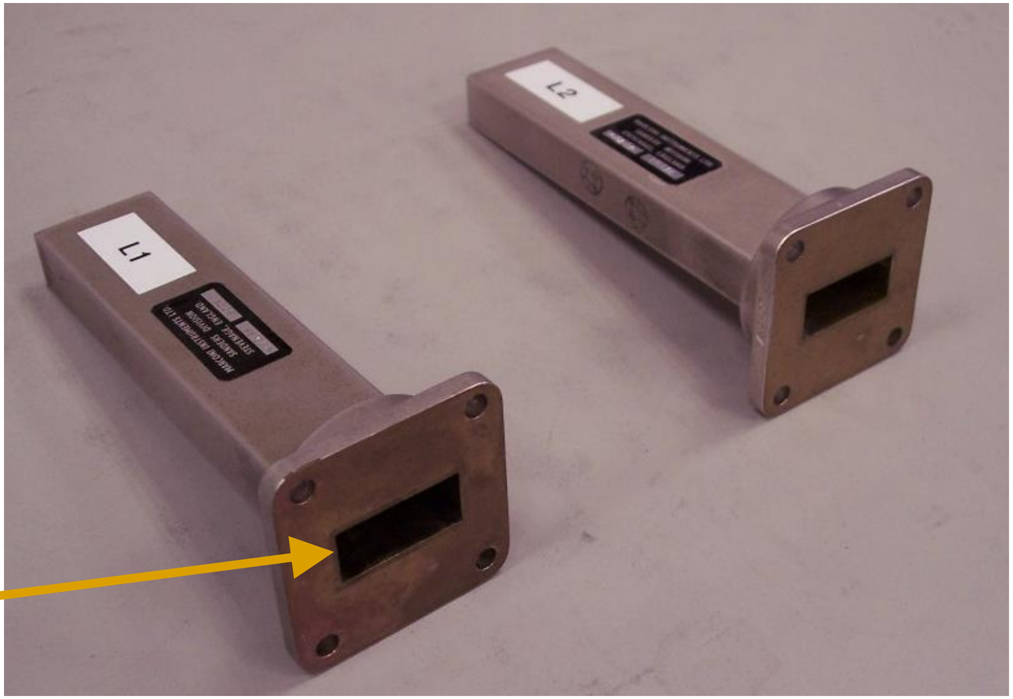
New measurements . . . going from GHz to THz

- **Instrumentation – waveguides**
- **Devices – on-wafer**

Metal waveguides – some history

- Use of metallic waveguide dates back to the early/mid 20th century
- First ‘popular’ waveguide: X-band (8.2 – 12.4 GHz)
- X-band aperture size:
  0.9″ × 0.4″
  23 mm × 10 mm



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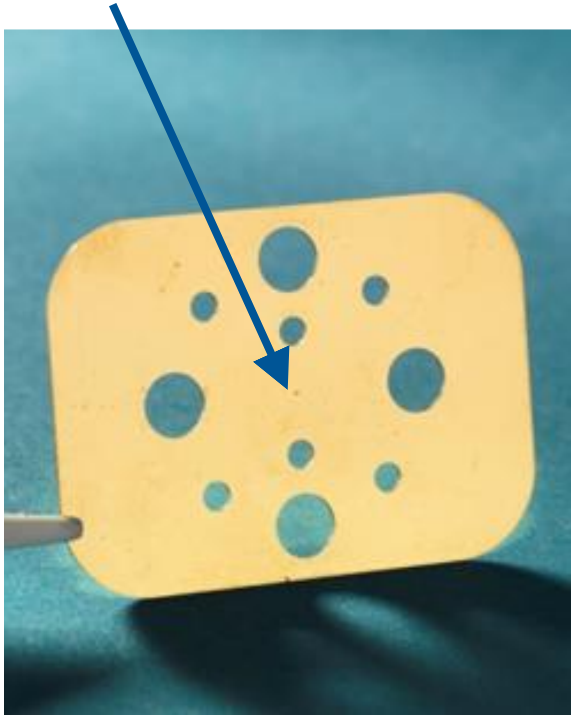
As frequencies get higher, waveguide gets smaller . . .

At 200 GHz
Aperture: 1.30 mm × 0.65 mm

At 1000 GHz (1 THz)
Aperture: 250 μm × 125 μm



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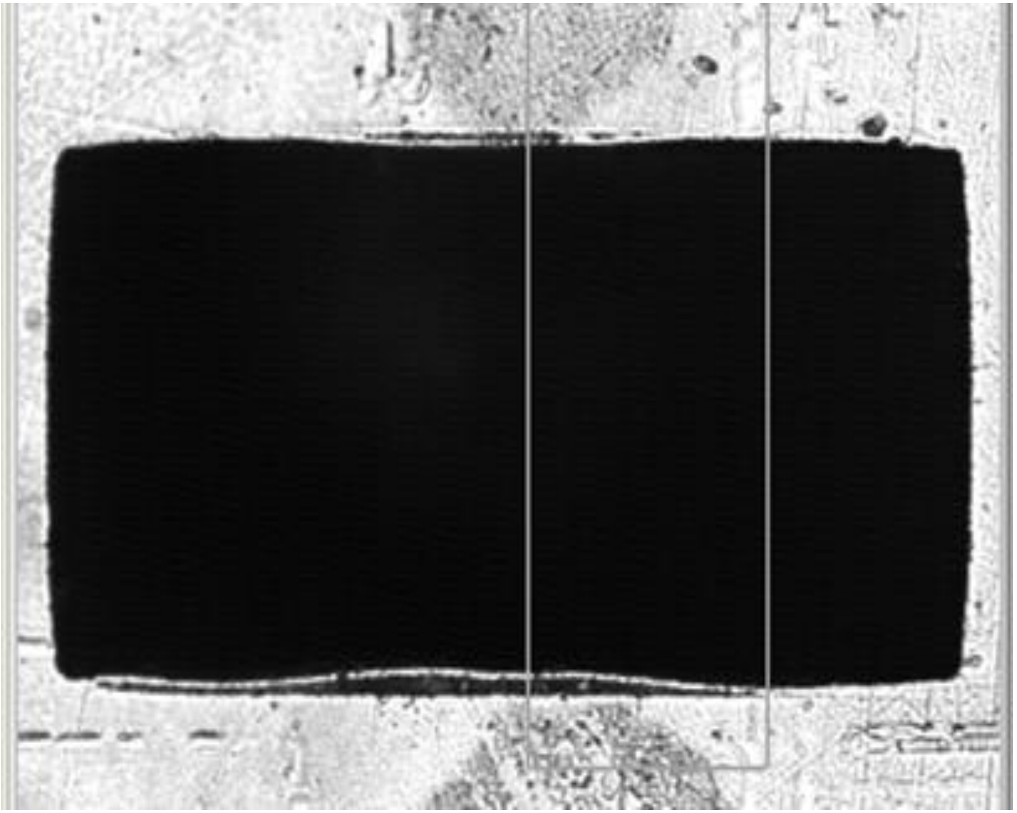
1 THz waveguide . . . seen under a microscope

(during a dimensional measurement)

Aperture =

250 μm × 125 μm



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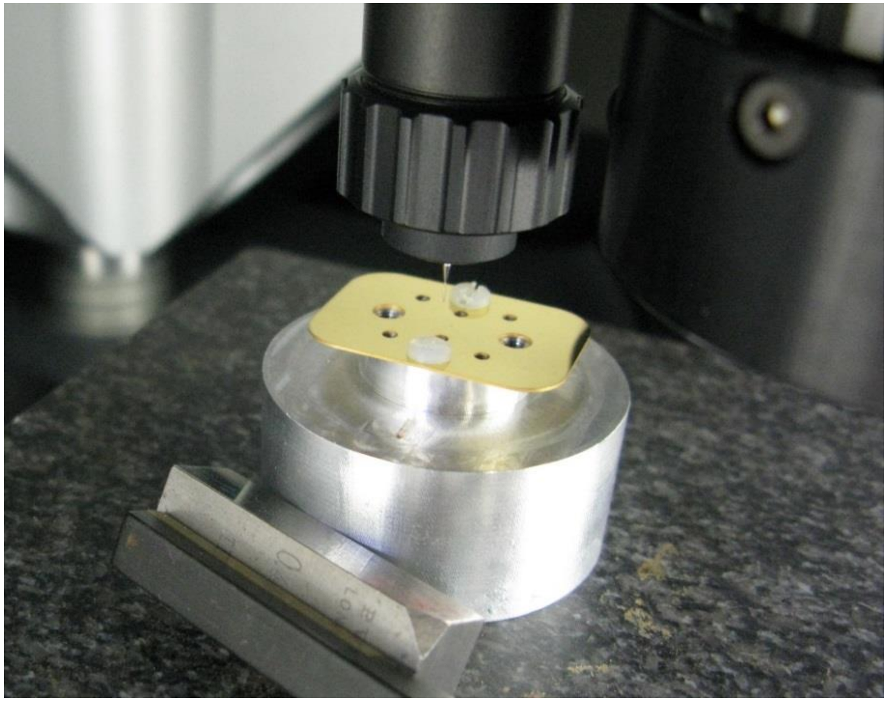
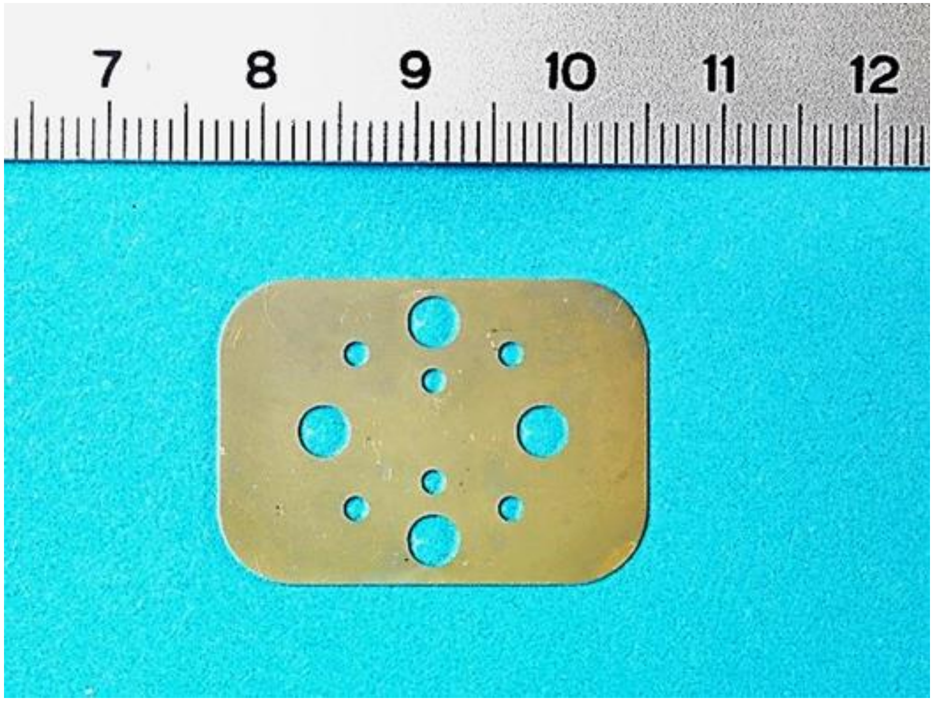
Dimensions measured using probe/vision systems

CMM (Coordinate Measuring Machines)

Waveguide apertures and flanges

New IEEE standards (1785)





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Three new standards:

"IEEE Standard for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above"

- IEEE Std 1785.1-2012
- IEEE Std 1785.2-2016
- IEEE Std 1785.3-2016

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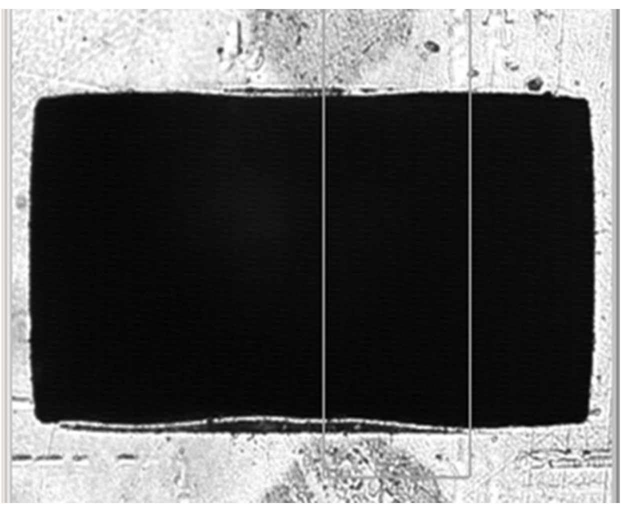
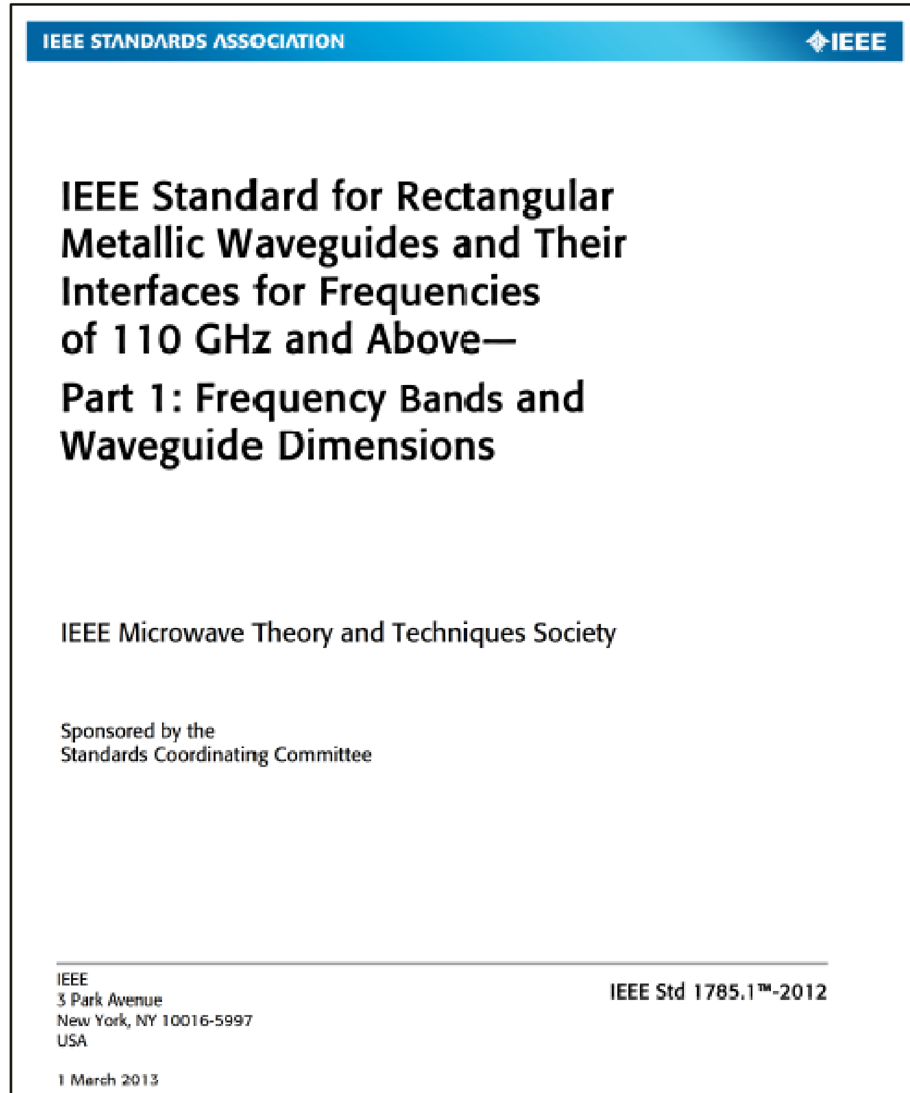
IEEE Std 1785.1-2012

Part 1: “Frequency Bands and Waveguide Dimensions”





IEEE STANDARDS ASSOCIATION IEEE

IEEE Standard for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above—

Part 1: Frequency Bands and Waveguide Dimensions

IEEE Microwave Theory and Techniques Society

Sponsored by the
Standards Coordinating Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

1 March 2013

IEEE Std 1785.1™-2012

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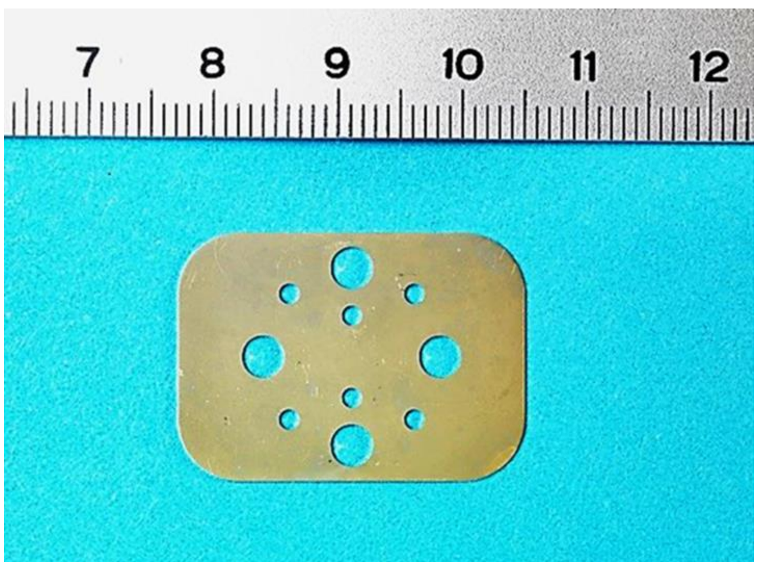
IEEE Std 1785.2-2016

Part 2: “Waveguide Interfaces”



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IEEE Standard for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above—

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IEEE Std 1785.3-2016

Part 3:

"Recommendations for Performance and Uncertainty Specifications"

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IEEE Recommended Practice for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above—

Part 3: Recommendations for Performance and Uncertainty Specifications

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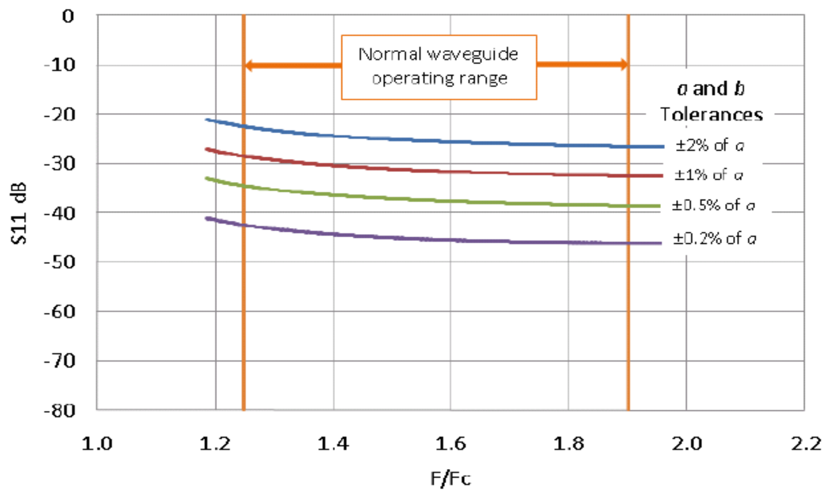
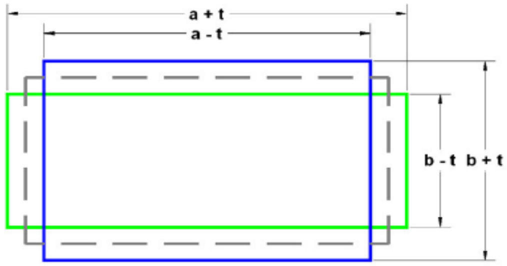
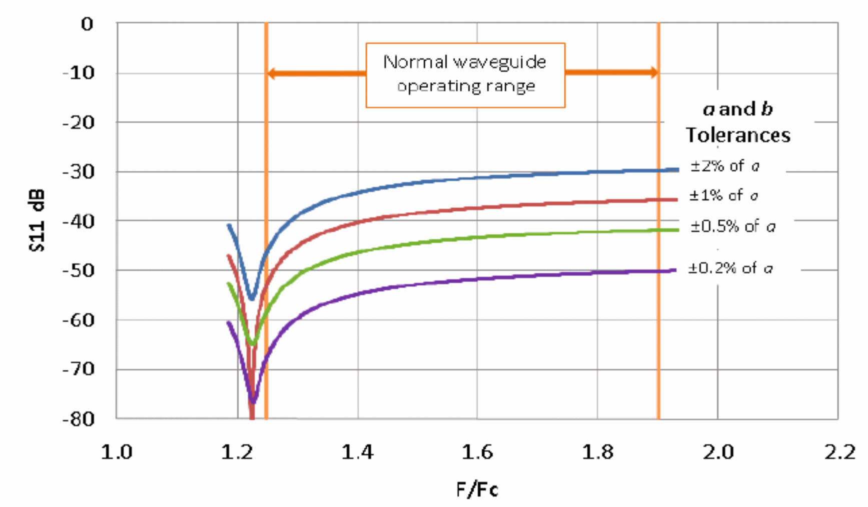
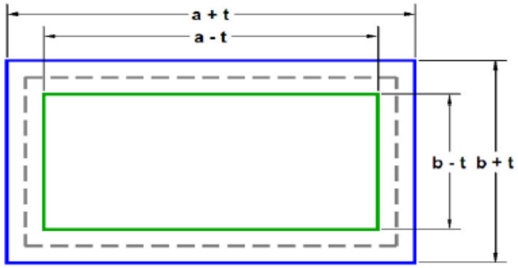
Effects of waveguide aperture and interface tolerances









Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

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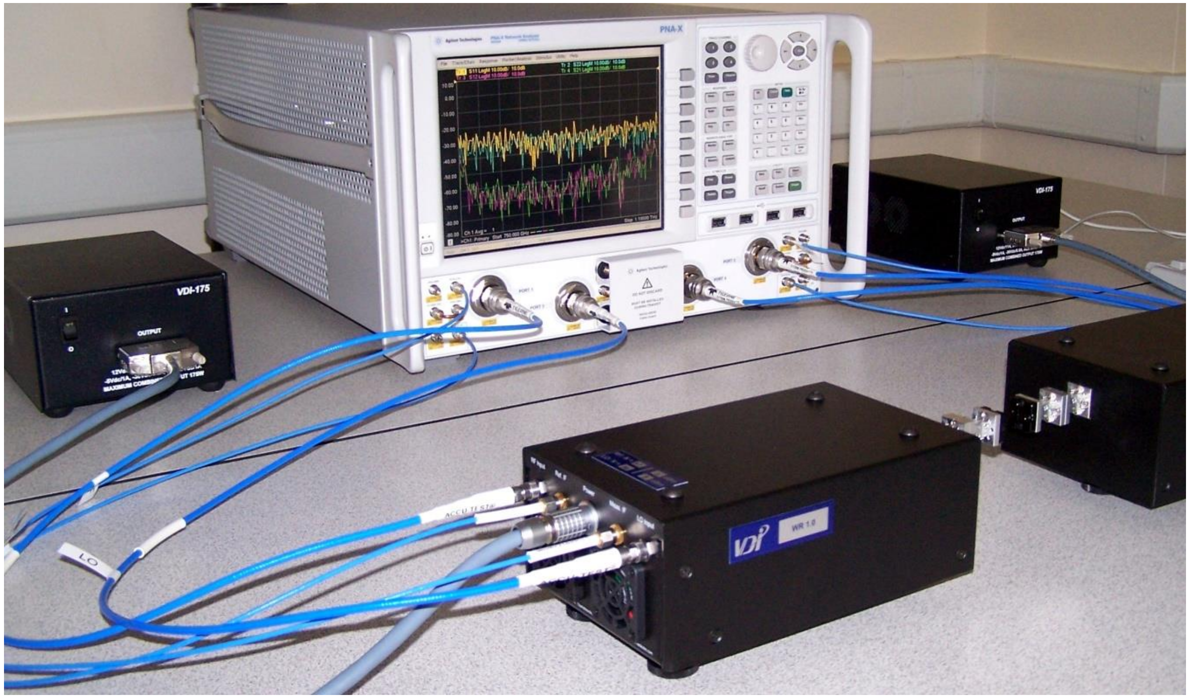
Waveguide measurement capability

- Vector Network Analyser (VNA) with high precision calibration kits
- University of Leeds / NPL partnership: Traceable VNA to 1.1 THz



Source: N M Ridler and R G Clarke, IEEE T-TST, 6 (1):2-11, Jan 2016.

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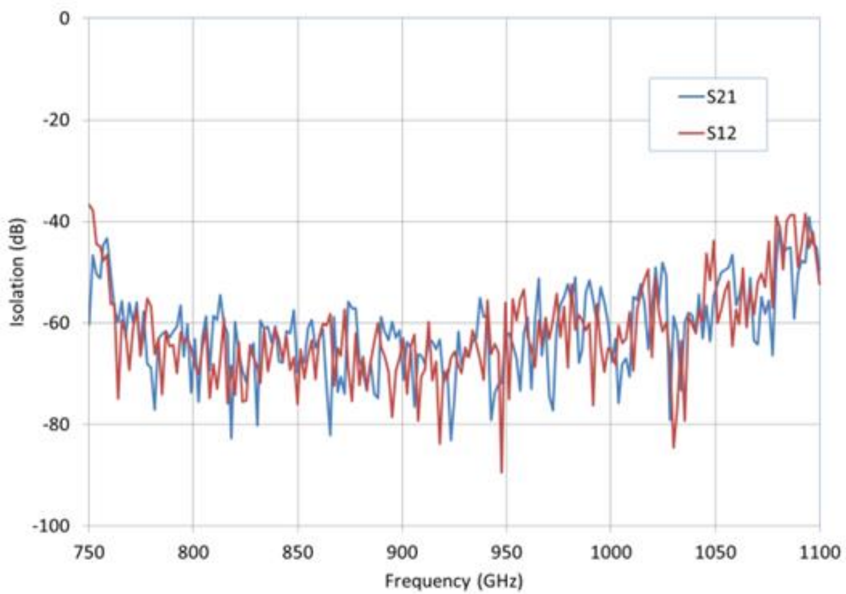
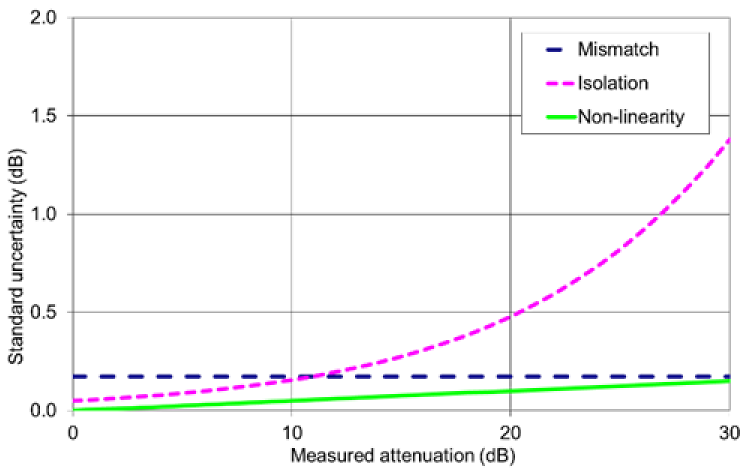
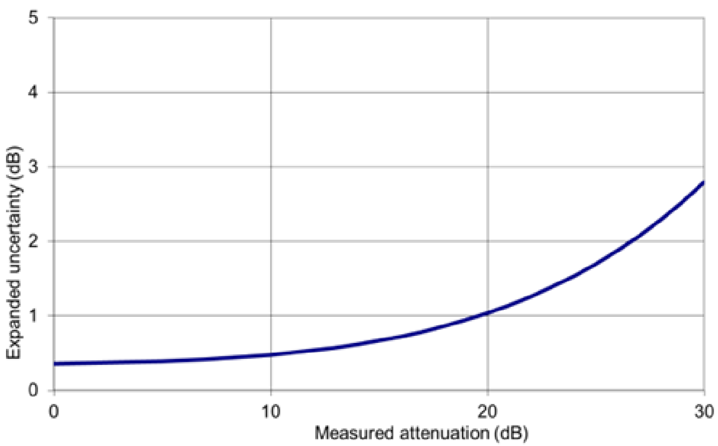
University of Leeds / NPL traceable measurements to 1.1 THz

VNA dynamic range (60 dB)



VNA accuracy (3 dB @ 30 dB)





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Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

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Filling the gap between microwaves and photonics

Remaining challenges:

- Key Comparisons and CMCs in the 0.1 THz to 1.0 THz range
- Establish traceability services offering *comprehensive* frequency coverage
- Establish *regional* metrology facilities – in Asia, Europe, North America, etc
- What about > 1 THz ??

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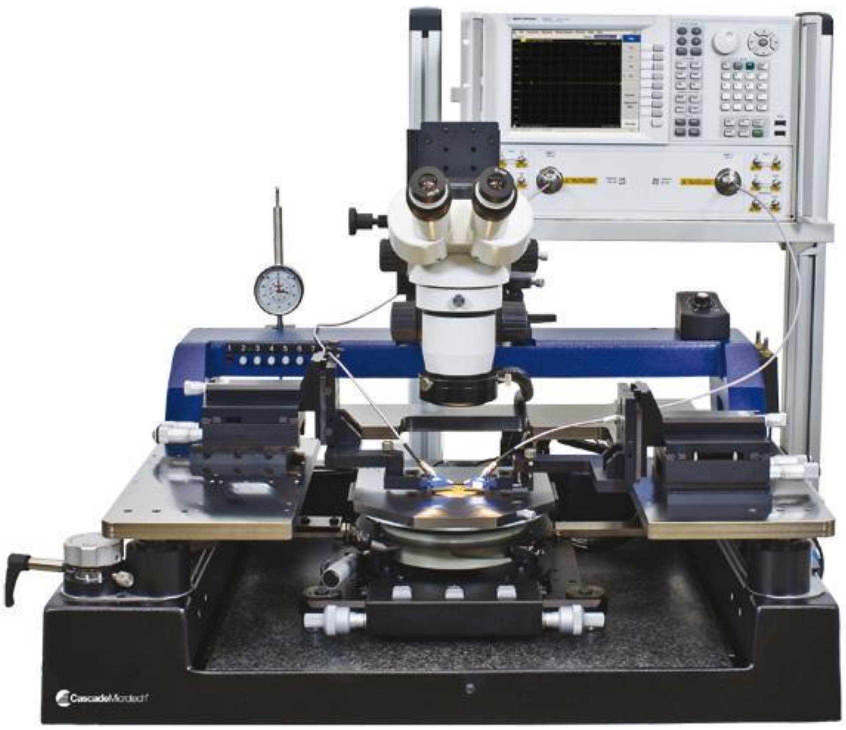
New measurements . . . going from GHz to THz

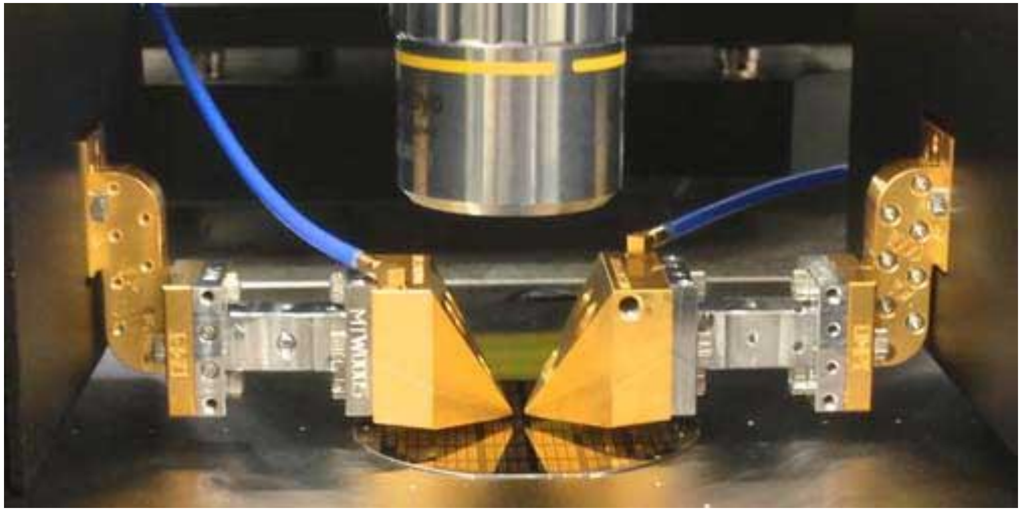
- Instrumentation – waveguides
- Devices – on-wafer

Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

Most devices are on a planar wafers

- We need a probe station and on-wafer probes to do measurements





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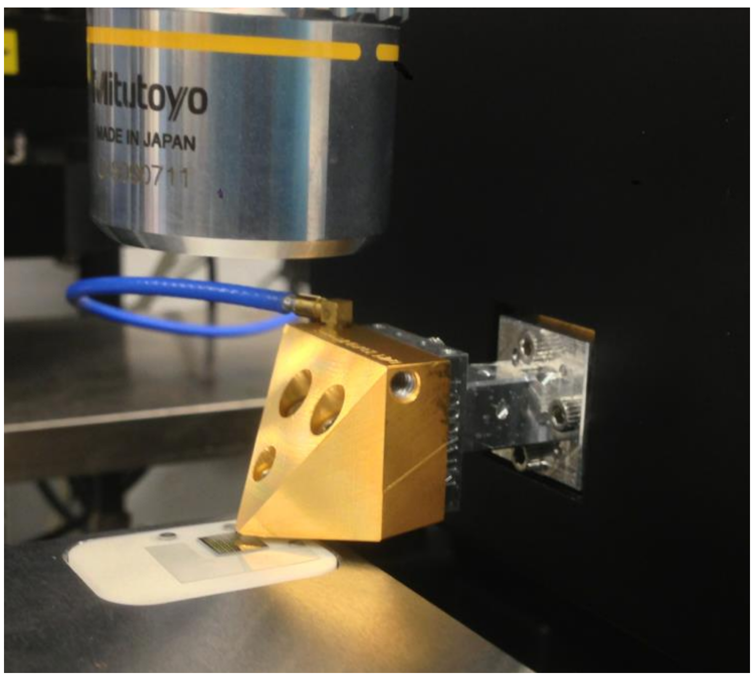
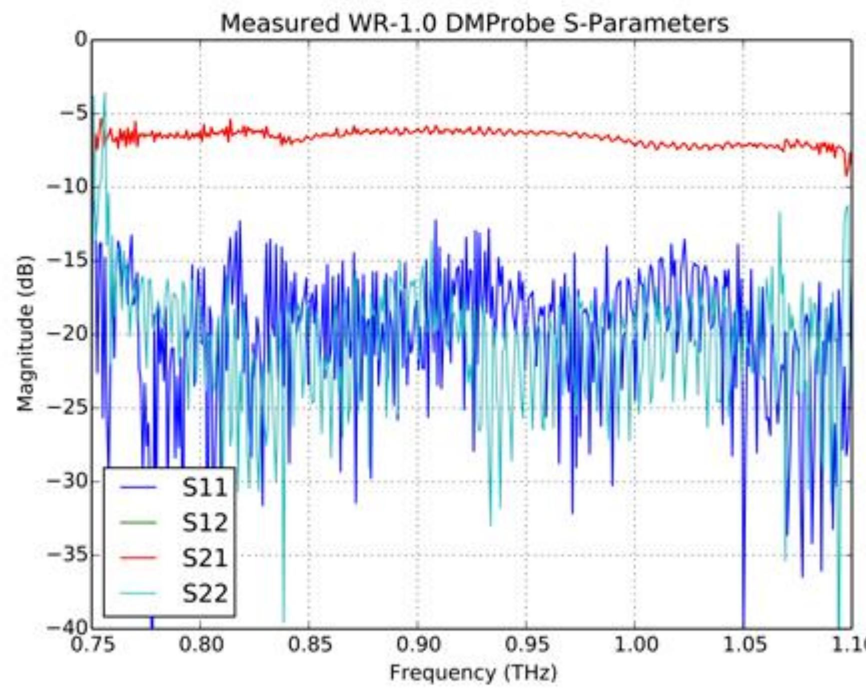
For on-wafer measurements, best to calibrate at probe tips using on-wafer standards: 750 GHz to 1.1 THz





Source: Dominion MicroProbes Inc (DMPI) web-site: www.dmprobes.com

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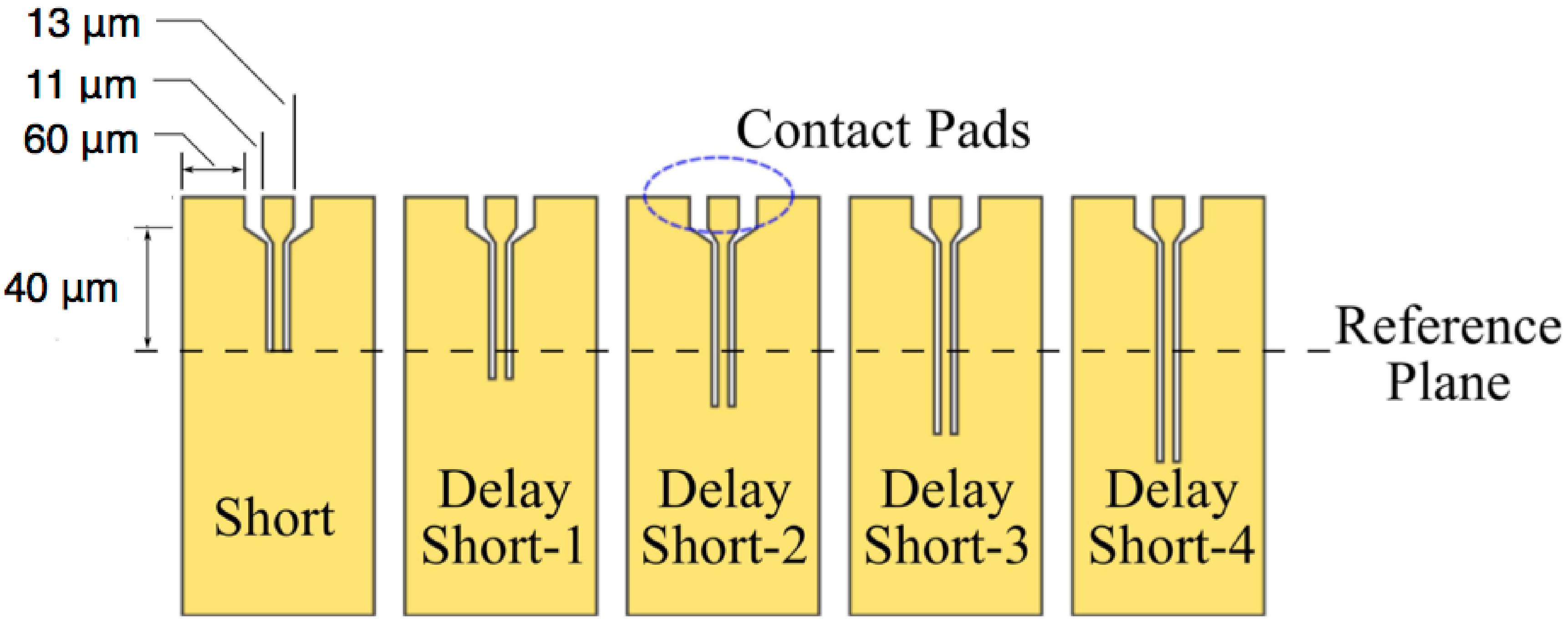
- On-wafer calibration kits (calibration substrates)



Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

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Filling the gap between microwaves and photonics

Remaining challenges:

- Measurement traceability!! . . . Yes or no??
  (there is still no on-wafer traceability, even after >25 years)
- Many scientific challenges relating to very short wavelength propagation
- Many technological challenges due to differing dimensions and materials
- Establish ***regional*** metrology capabilities – in Asia, Europe, North America, etc

Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

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Next topic . . .

I. Filling the gap between microwaves and photonics

II. **Multi-physics – more than just microwaves**

III. When digital becomes analogue

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Multi-physics – more than just microwaves

Application area . . .

Telecommunications

- 5G and beyond
- Machine to Machine (M2M)
- Internet of Things (IoT)
- RF Nano-technology

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The start of the communications revolution . . .

Alexander Graham Bell at the opening of the long-distance telephone line from New York to Chicago in 1892

(125 years ago)

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Modern communications devices (power amplifiers, etc) require an holistic (multi-physics) approach to device testing

- Microwave measurements

  . . . and

- Electromagnetic near-field scanning

  . . . and

- Thermal imaging

It would be great to do all this, at the same time !!

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This approach is available at **n3m-labs** (the Nonlinear Microwave Measurement & Modelling Laboratories) at the University of Surrey and NPL in the UK

n3m-labs was opened in June 2016

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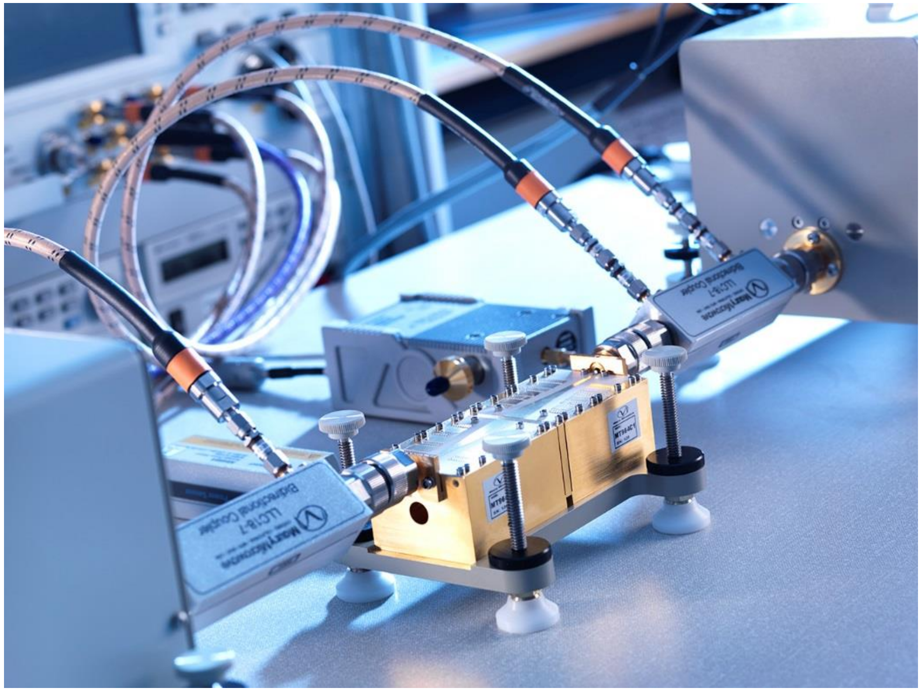
Fixtured microwave measurements – large-signal; passive/active harmonic loadpull



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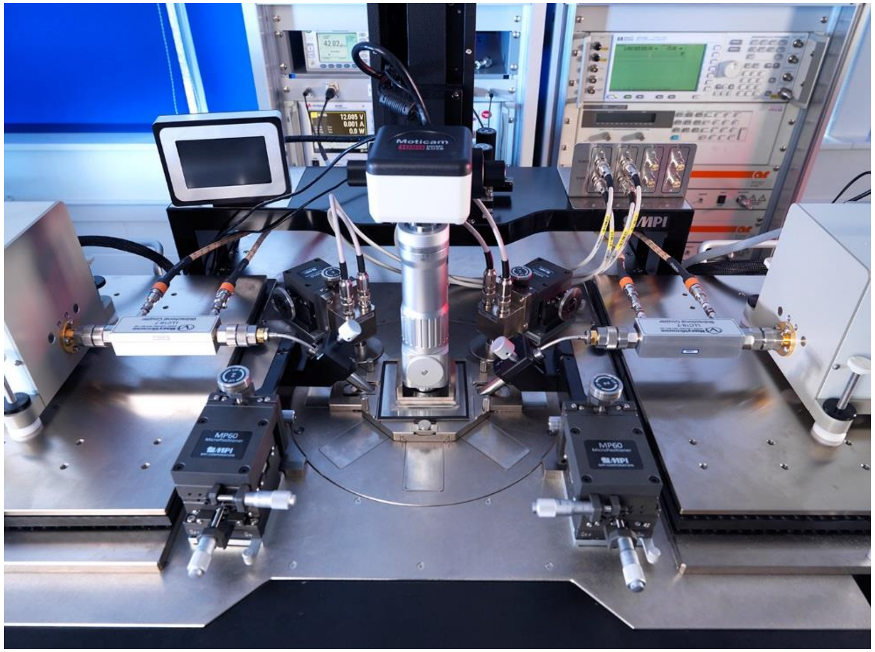
On-wafer microwave measurements – large-signal; passive/active harmonic loadpull



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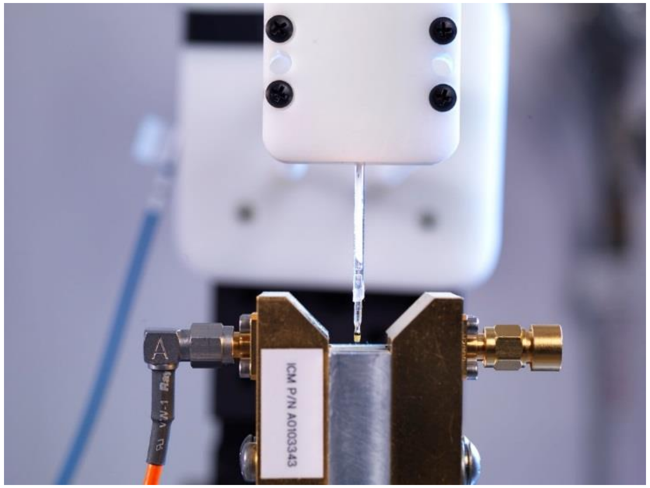
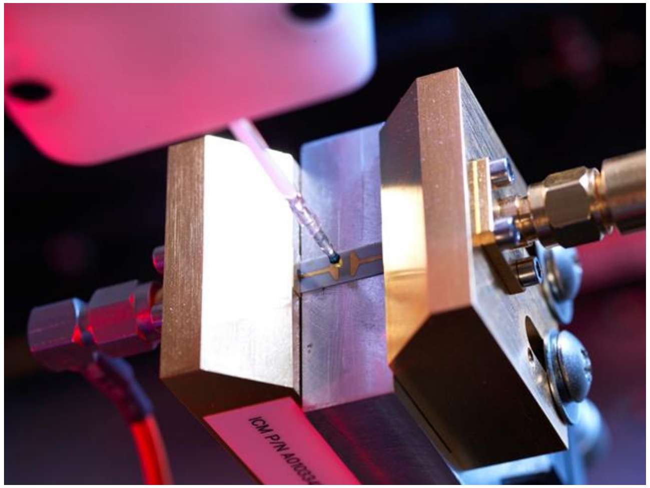
Electromagnetic near-field scanning





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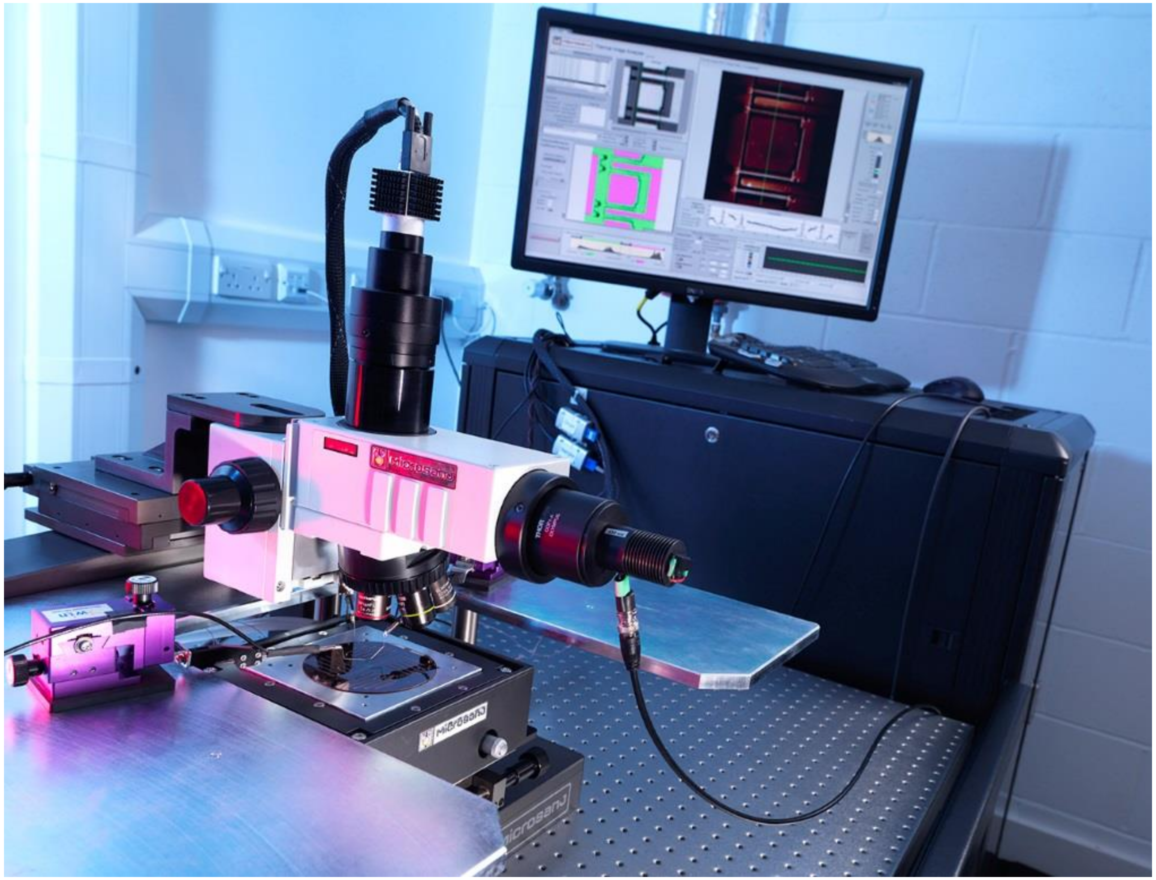
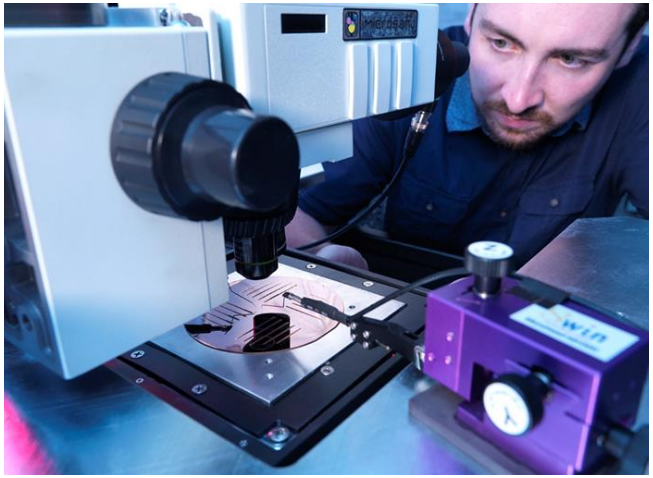
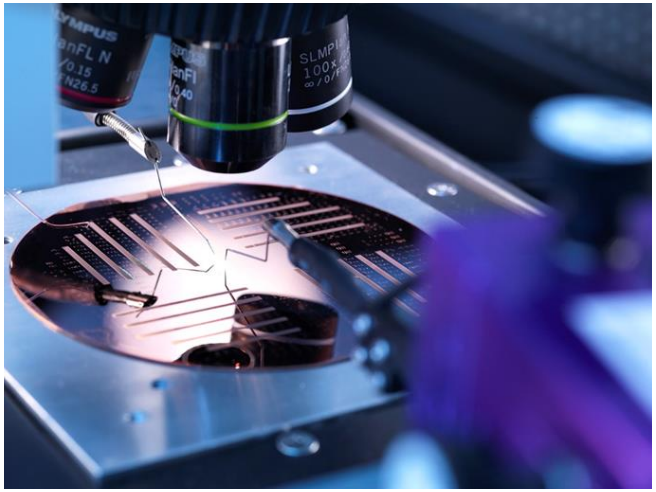
Thermal imaging







Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

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n3m-labs capabilities:

- On-wafer/fixtured passive/active harmonic loadpull
- Two Nonlinear VNAs to 67 GHz
- High power RF sources
- On-wafer probe station (temperature: –40 °C to +200 °C)
- High-resolution thermal imaging (0.25 um and 50 ns)
- Near-field electromagnetic scanner
- Nonlinear device modelling software
- Compute cluster: 1064 cores, 5.5 TB RAM, GPUs…
- UK primary national measurement standards

n3m-labs

Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

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Multi-physics – more than just microwaves

Remaining challenges :

- Traceability for ‘new’ non-linear measurands (X-parameters, etc)
- Source-pull and Load-pull measurements ($Z_0 \neq 50$ ohms)
- Uncertainties in measurement-derived models
- Measurement site-to-site reproducibility

Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

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Final topic . . .

I. Filling the gap between microwaves and photonics

II. Multi-physics – more than just microwaves

III. **When digital becomes analogue**

Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

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When digital becomes analogue

Applications:

- Computing
- Internet of Things (IoT)
- High-speed electronics (interconnects)
- Games (Wii, Playstation, Xbox)

Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

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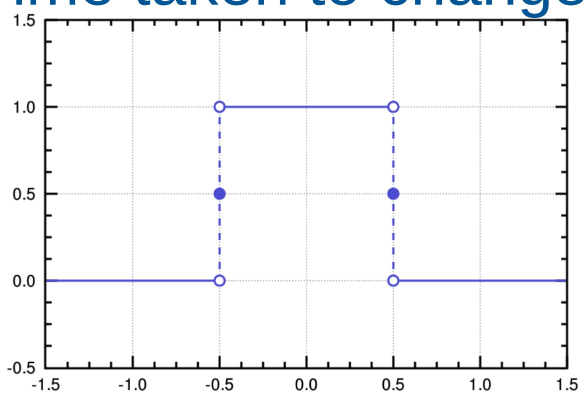
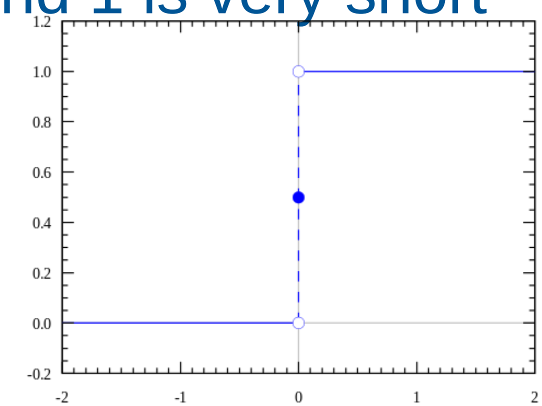
Key technology: Printed Circuit Boards (PCBs) and component interconnects

- Digital signals (ones and zeros: 1, 0, 0, . . ., 0, 1, . .)
- Time taken to change between 0 and 1 is very short

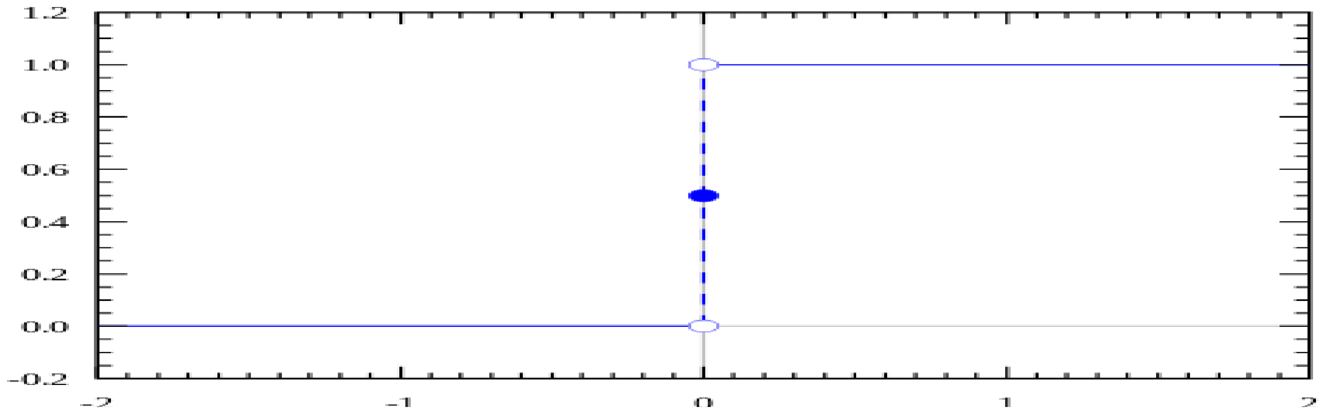


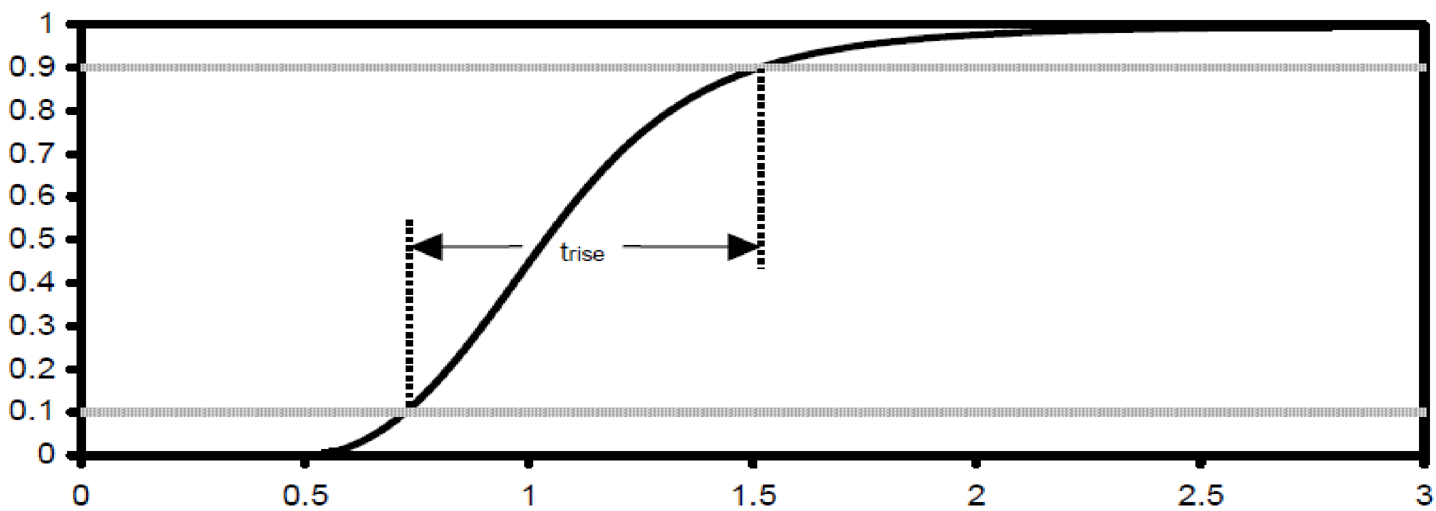


- Leading edge contains many high frequency components

Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

1. Pulse risetime





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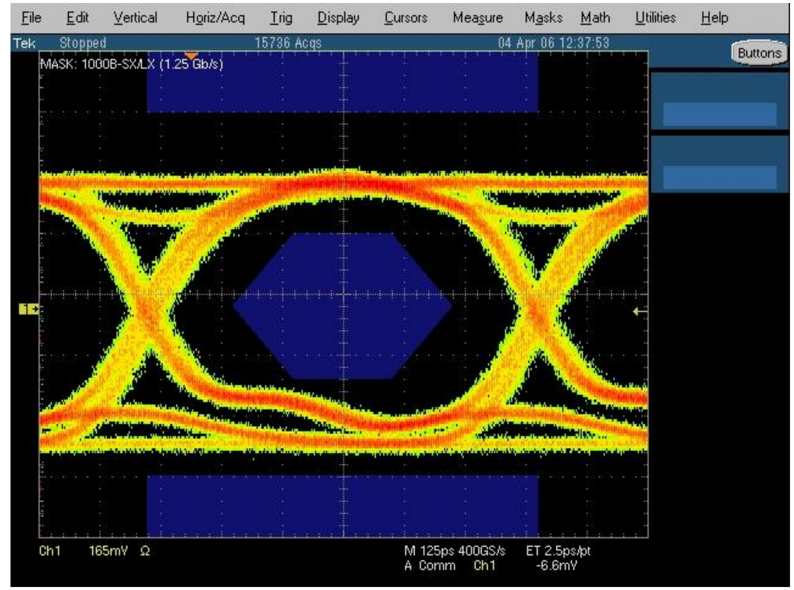
Risetime (seconds):
bandwidth (hertz)

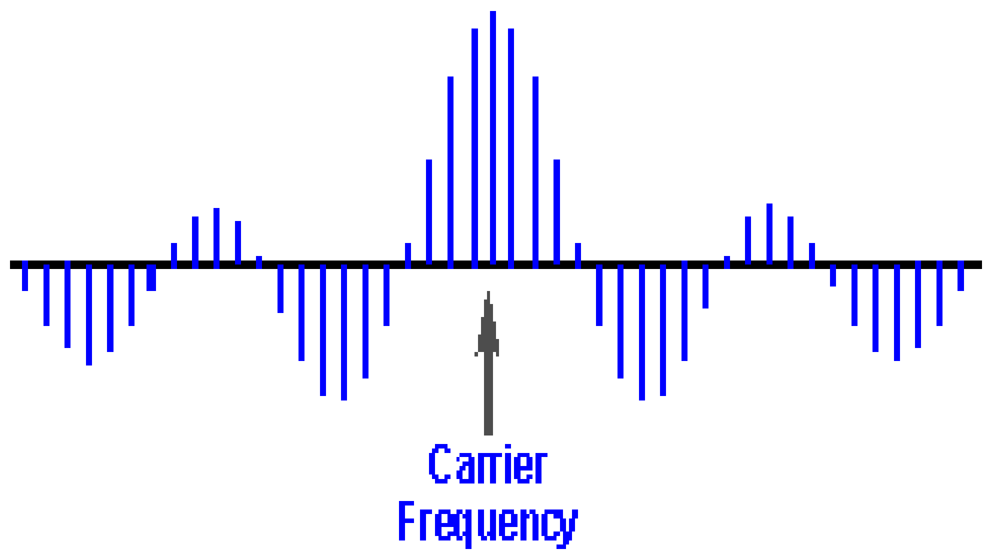
$$RT = \frac{0.35}{BW}$$



Risetime = 10 ps

Bandwidth = **35 GHz**

mm-wave frequencies!



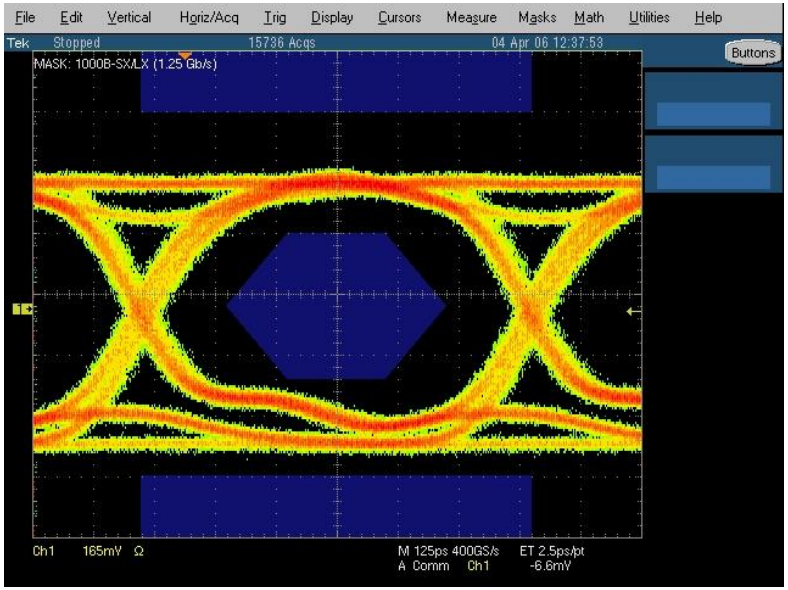
Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

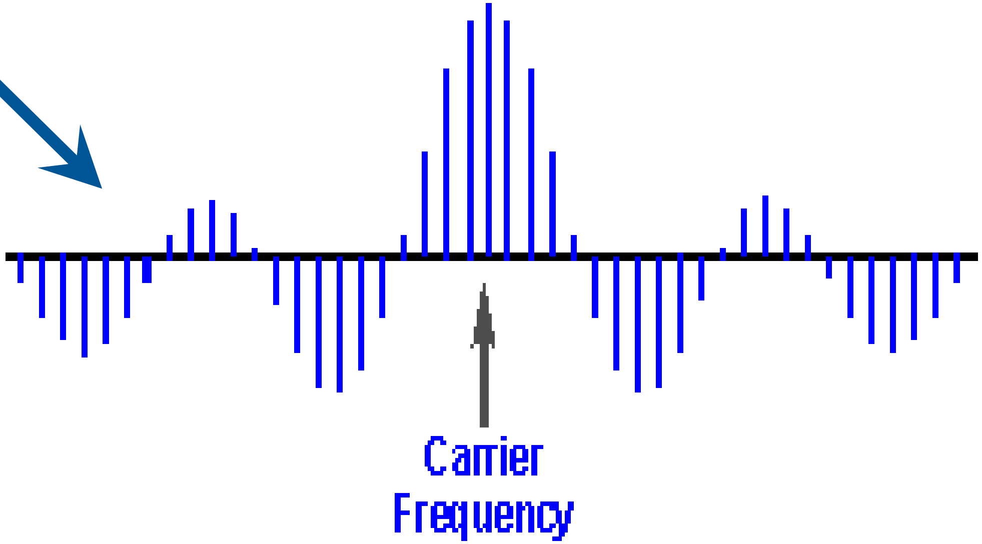
For measurements, we need:

Time-domain

and

Frequency-domain





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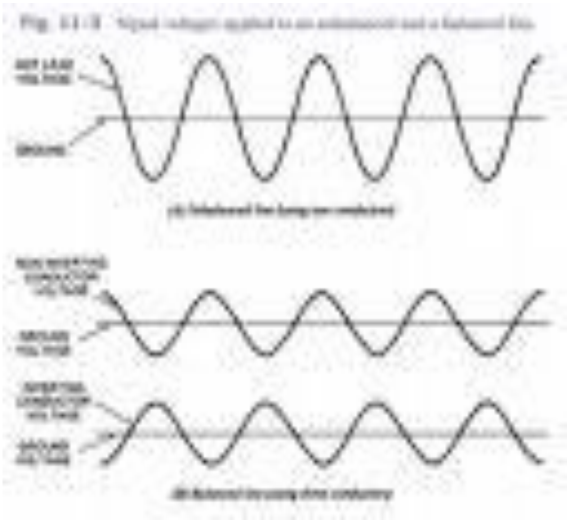
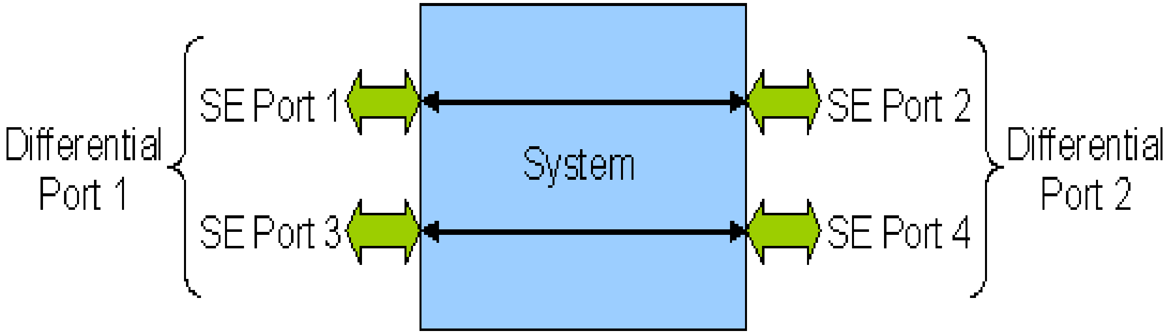
2. PCB component packing/interconnect – very high density

- Use differential signals to avoid component-to-component interference





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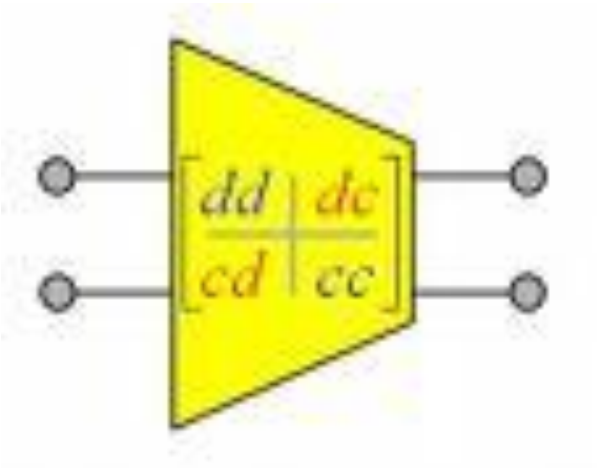
For measurements, we need:



Mixed-mode *S*-parameters:

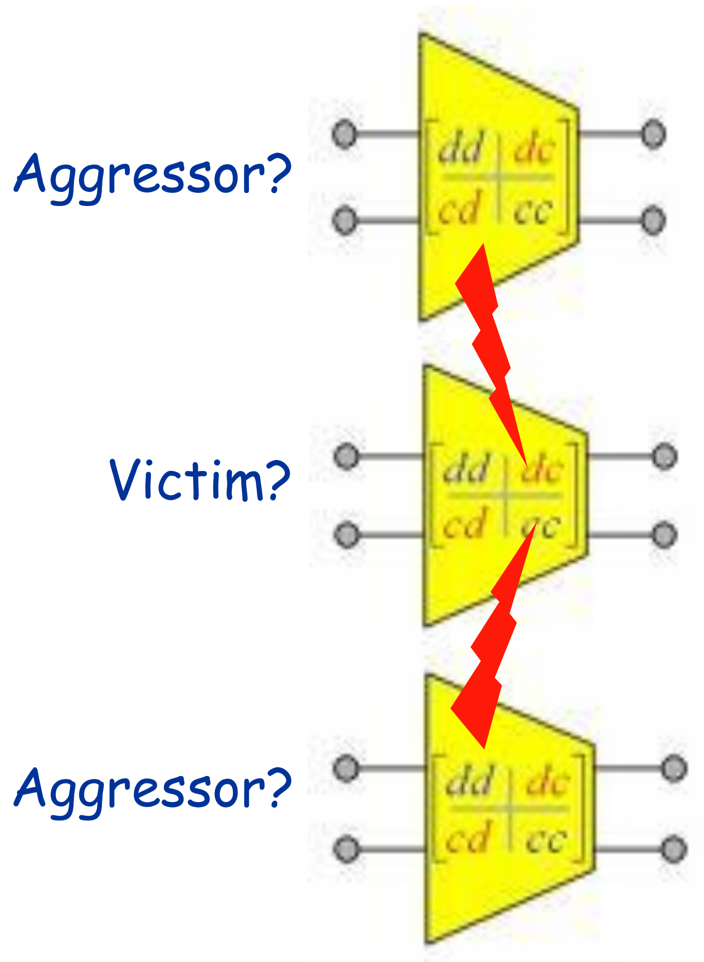
- Differential-mode (DD)
- Common-mode (CC)
- Mode conversion: differential-to-common and vice versa (CD, DC)

$$\begin{pmatrix} S_{DD,11} & S_{DD,12} & S_{DC,11} & S_{DC,12} \\ S_{DD,21} & S_{DD,22} & S_{DC,21} & S_{DC,22} \\ S_{CD,11} & S_{CD,12} & S_{CC,11} & S_{CC,12} \\ S_{CD,21} & S_{CD,22} & S_{CC,21} & S_{CC,22} \end{pmatrix}$$

Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

Component interference “victims” and aggressors”

- 3 devices
- Each device has 4 connections
- We need 12 “ports” to make these measurements



Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

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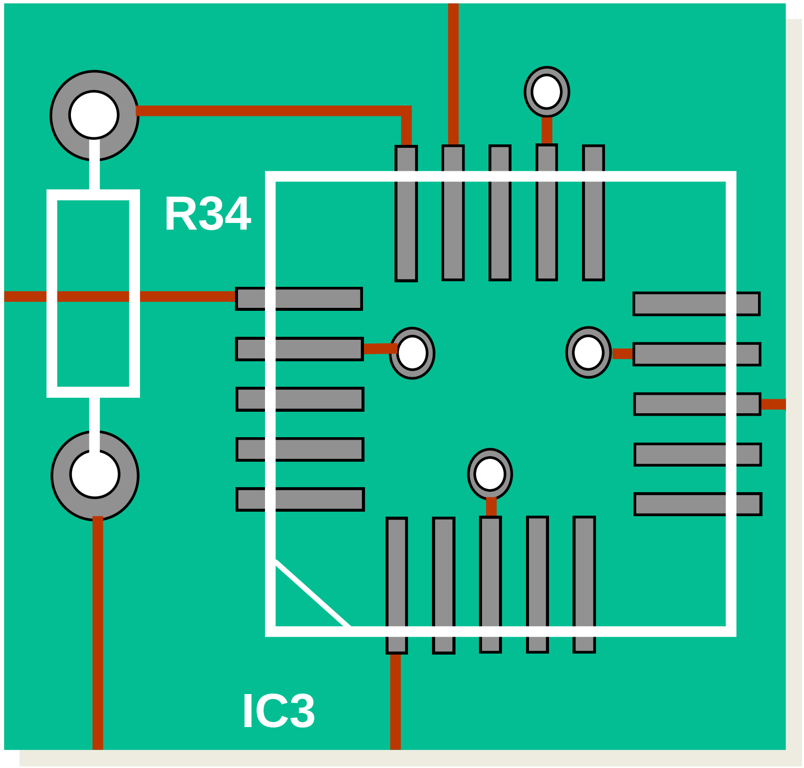
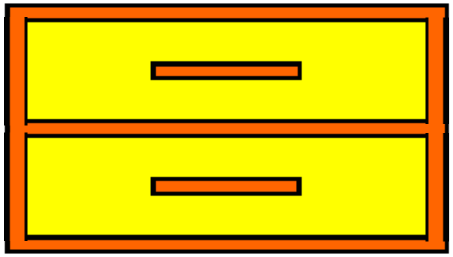
3. Multilayer PCBs

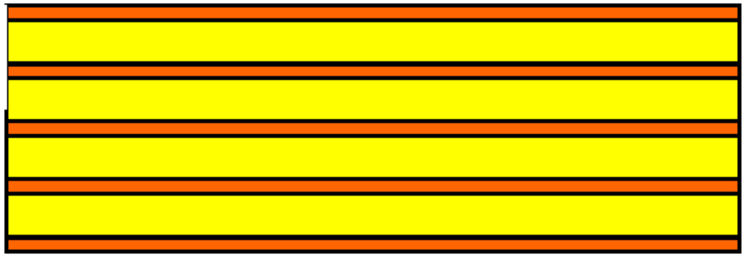
- Involves conductors and dielectrics sandwiched together
- Connections to embedded layers are difficult
- Via holes are drilled through layers to help with interconnects

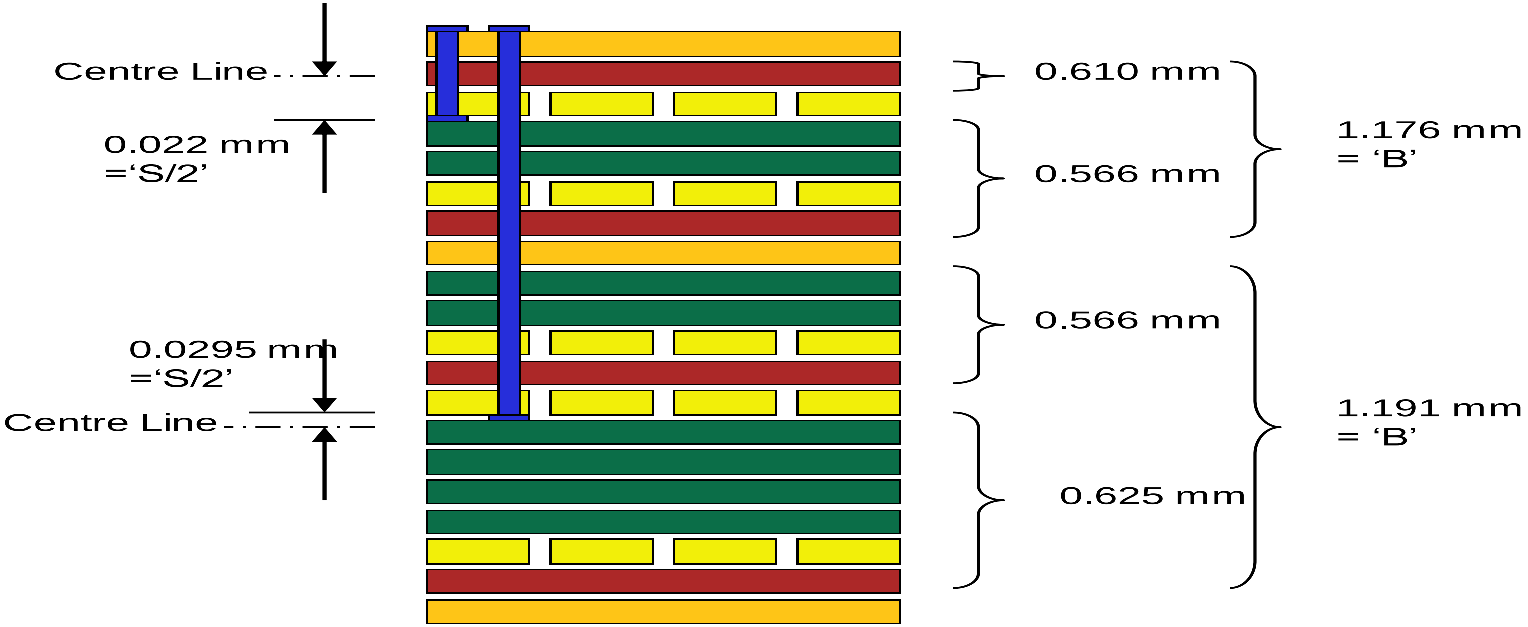


Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

Multi-layer PCBs







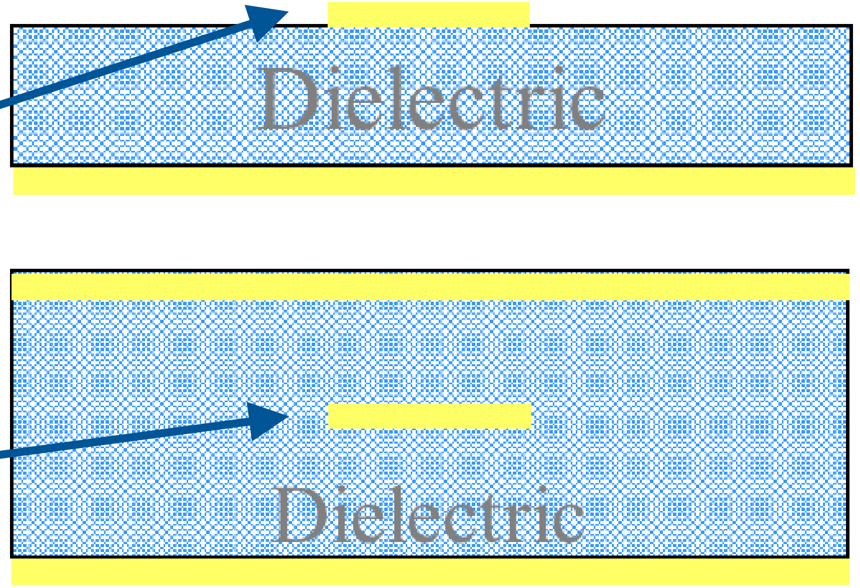
Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

NPL National Physical Laboratory

PCBs with several layers

Two types of transmission line:

- Microstrip
- Stripline



Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

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Combined measurement architecture:

- Time-domain / Frequency-domain – for Signal Integrity assessments
- Differential signals – mixed-mode *S*-parameters
- Multi-port devices – for victims and aggressors assessments
- Multi-layer microstrip / stripline transmission lines

Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

NPL National Physical Laboratory

Remaining challenges – when digital becomes analogue:

- Traceability and/or Best Practice on PCBs:
    - Time-domain / Frequency-domain equivalence
    - Mixed-mode S-parameters
    - Multi-layer PCBs
- Provide input to industry-level standards-making: IEEE (P370), IPC (TM650), etc
- 'Wire' interconnects at the nano-scale
- Establish ***regional*** metrology capabilities – in Asia, Europe, North America, etc

Future challenges in high-frequency electromagnetic metrology (RF to terahertz)

Topics I haven’t discussed (but are still very important):

- Terahertz time-domain systems (spectrometers, etc)
- Antenna beam-forming techniques for mm-wave communications
- Extreme impedance measurements for emerging nano-materials (graphene, etc)

Further reading – THz metrology

National Physical Laboratory

- *The 2017 Terahertz Science and Technology Roadmap*

  46 co-authors, J Phys D, Vol 50, No 4, 043001 (49pp), Feb 2017

- *Metrology State-of-the-art and Challenges in Broadband Phase-sensitive Terahertz Measurements*

  M Naftaly, R G Clarke, D A Humphreys, N M Ridler, Proc IEEE, Jan 2017

- *Establishing Traceability to the International System of Units for Scattering Parameter Measurements from 750 GHz to 1.1 THz*

  N M Ridler, R G Clarke, IEEE Trans TST Vol 6, No 1, pp 2-11, Jan 2016

- *Terahertz Metrology*

  Mira Naftaly (Editor), Artech House, 2015