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

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

Focus on three ‘new’ measurement topics . . .

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

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

III. **When digital becomes analogue**
Focus on three ‘new’ measurement topics . . .

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

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

Filling the gap between electronics and photonics
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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

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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”
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IEEE Std 1785.2-2016

Part 2: “Waveguide Interfaces”
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IEEE Std 1785.3-2016

Part 3:

“Recommendations for Performance and Uncertainty Specifications”
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Effects of waveguide aperture and interface tolerances
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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

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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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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
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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)
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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
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Next topic . . .

I. Filling the gap between microwaves and photonics

II. Multi-physics – more than just microwaves

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

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

**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
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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 \( (Z_0 \neq 50 \text{ ohms}) \)
- Uncertainties in measurement-derived models
- Measurement site-to-site reproducibility
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Final topic . . .

I. Filling the gap between microwaves and photonics

II. Multi-physics – more than just just microwaves

III. When digital becomes analogue
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When digital becomes analogue

Applications:

- Computing
- Internet of Things (IoT)
- High-speed electronics (interconnects)
- Games (Wii, Playstation, Xbox)
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Key technology: Printed Circuit Boards (PCBs) and component interconnects

- Digital signals (ones and zeros: $1, 0, 0, \ldots, 0, 1, \ldots$)

- Time taken to change between 0 and 1 is very short

- Leading edge contains many high frequency components
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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!
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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)
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Component interference “victims” and aggressors

- 3 devices
- Each device has 4 connections
- We need 12 “ports” to make these measurements
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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
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Multi-layer PCBs
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PCBs with several layers

Two types of transmission line:

- Microstrip
- Stripline
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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
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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
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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

- *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