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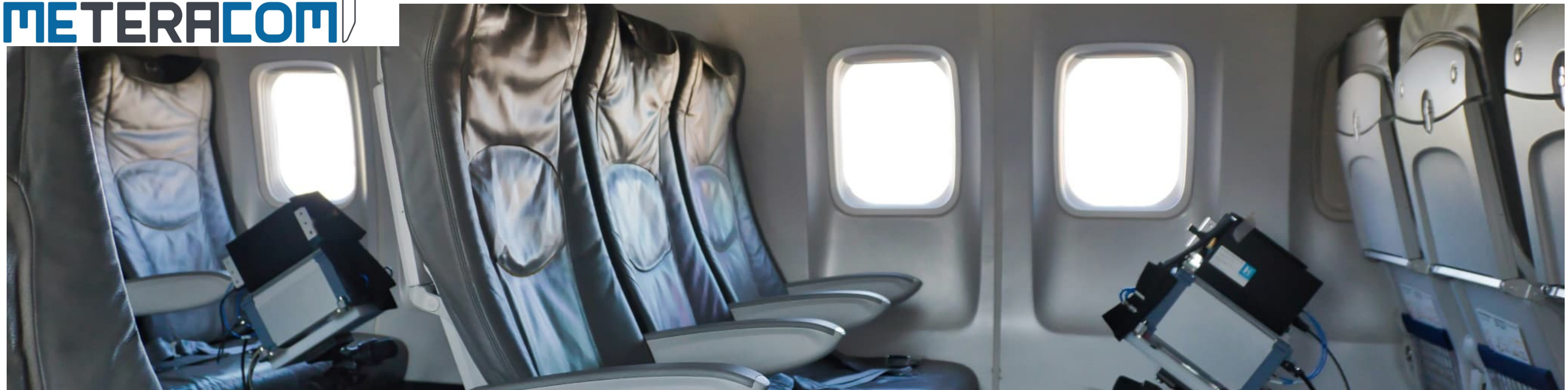
**FOR 2863 Meteracom**
**Metrology for THz Communications**

The 50th International Conference on Infrared, Millimeter, and Terahertz Waves
17-22 August, 2025

METERACOM



# Development considerations for traceability of h-band THz communication waveforms

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DFG FOR2863 Meteracom Final Workshop @ IRmmW-THz 2025, 20 August 2025

# Overview

- Traceability for modulated waveforms – options and requirements
- Evaluation of an existing prototype device
  - Proof of principle
  - Modelling
- Improving the design to meet the traceability requirements
  - Antenna behaviour
  - Frequency flatness/measured results
- New prototype design
  - Modelling
  - Realising semi-infinite GaAs
  - Connection options
- Summary

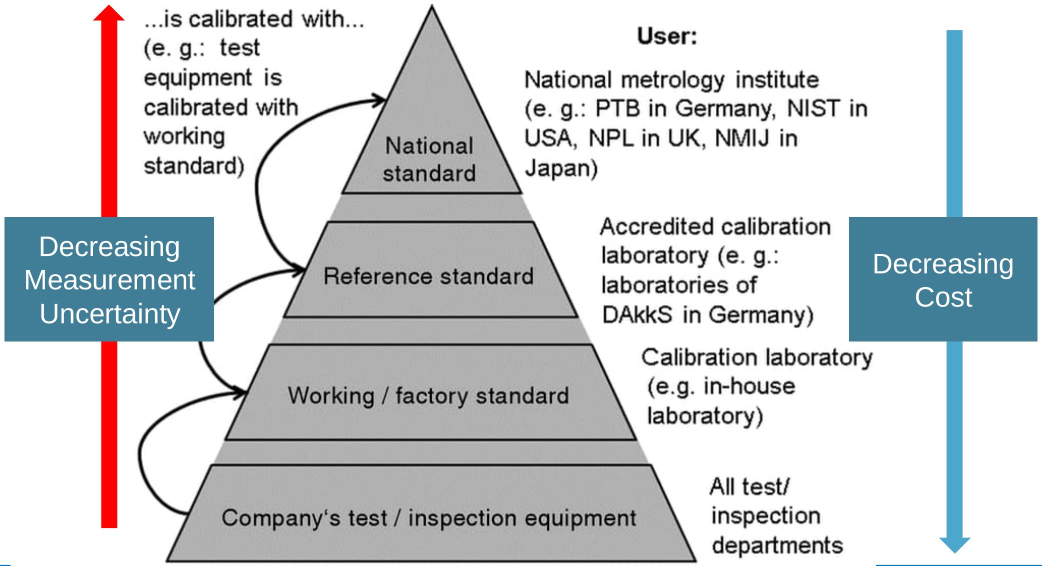
## Overview

- Traceability for modulated waveforms – options and requirements
- Evaluation of an existing prototype device
- Improving the design to meet the traceability requirements
- New prototype design
- Dual polarisation?
- Summary

# Traceability

- Metrological Traceability or Measurement Traceability is a " property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty." [1]
- Measurement traceability is important because it gives you confidence and assurance that your measurement results agree with national or international standards within the statement of uncertainty in measurement. Without traceability, a laboratory can claim anything they want in a test or calibration report.
- How do you achieve confidence in the result?








[1] BIPM, "VIM: International Vocabulary of Metrology - basic and general concepts and associated terms (2012)," Available at: https://doi.org/10.59161/JCGM200-2012

# Instrument-based approach to traceability

- Candidates:
- modulation capable VNA systems
- v(t) calibrated AWG + oscilloscope
- Limitations:
- v(t) comb and coaxial instrumentation limited to 165 GHz [2]

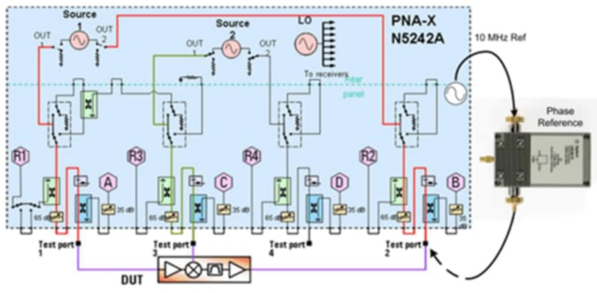
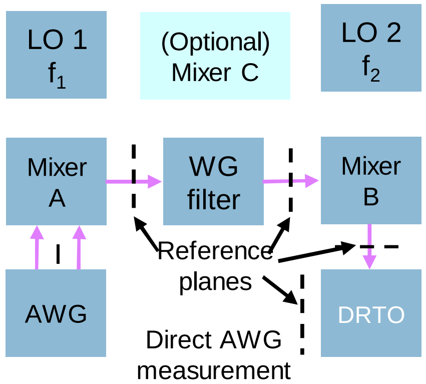



Figure 1: Mixer Measurement System Block Diagram

[3] Joel Dunsmore, "A New Calibration Method for Mixer Delay Measurements that Requires No Calibration Mixer", Proc. 41st European Microwave Conference, 11 Oct 2011 Also see Application note PNA-X 1408-23.

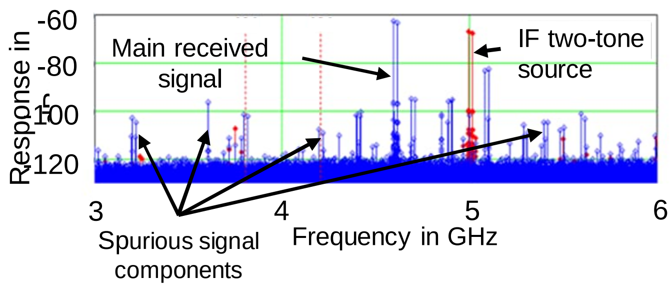
- Mixers can be used for up and down-conversion so identical devices can determine group delay
- Limitations:
- Inherently nonlinear – other terms present (visible if different IF frequencies used)
- Ideally, 3 or more devices required
- Overall: Good solution for industry and research applications




VNA can be used in place of AWG/RTDO

LO frequencies

| | |
|---|---|
| Up-conversion | 10.4975 GHz |
| Down-conversion | 10.6975 GHz |

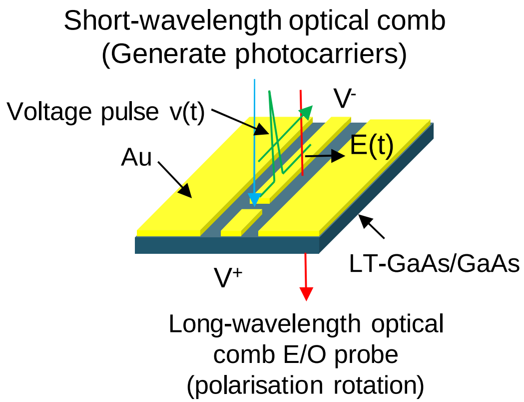




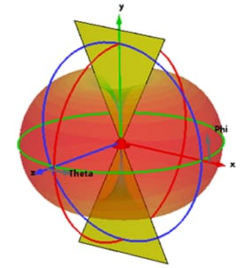

[2] A. Schramm, F. Gellersen, F. Rausche and K. Kuhlmann, "Traceable S-Parameter Measurements Up to 165 GHz Using 0.8 mm Coaxial Standards," in IEEE Microwave and Wireless Technology Letters, vol. 35, no. 6, pp. 936-939, June 2025, doi: 10.1109/LMWT.2025.3562419.

# Physics-based approach

- Suitable for NMI use
- Based on v(t) EOS/Photo-conductive switch knowledge
- Key requirements
  - Target operation at 100 GHz and 300 GHz
  - Sufficient operating bandwidth (5-10 GHz)
  - Frequency/phase flat over operating frequency range
  - Good antenna characteristics
  - Some way to independently test the device (EOS)
  - Device can be modelled
- Operation
  - Current across the photoconductor gap is proportional to the voltage(t) across the gap, Each RF frequency component is down-converted to ±38 MHz baseband

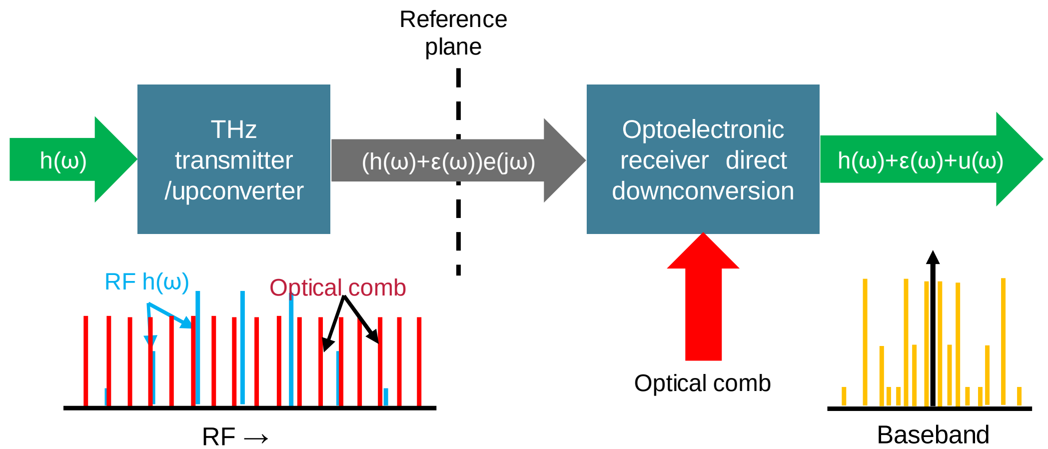



Generic photoconductive pulse generator and Electro-Optic sampler



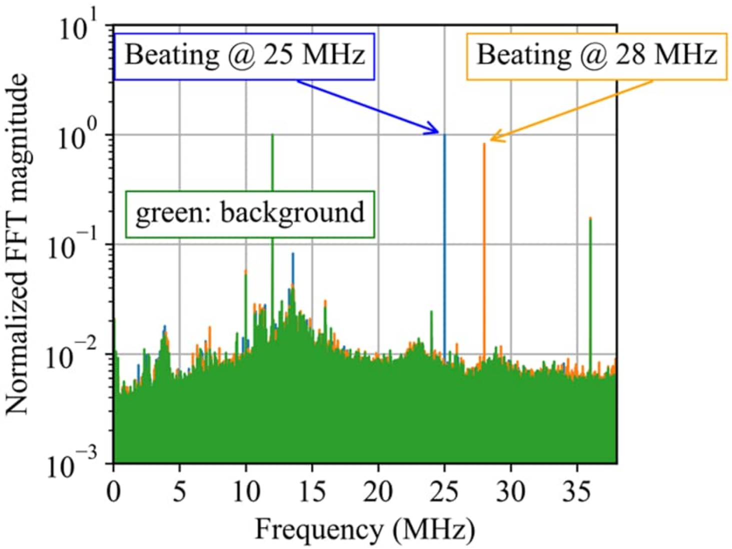
Bow-Tie antenna has a wider bandwidth than a simple dipole antenna

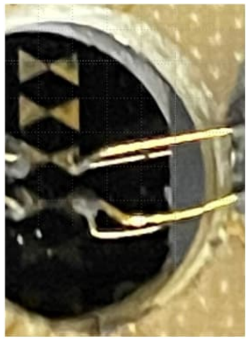
In free-space the polar radiation diagram appears to be smooth and free from strong features

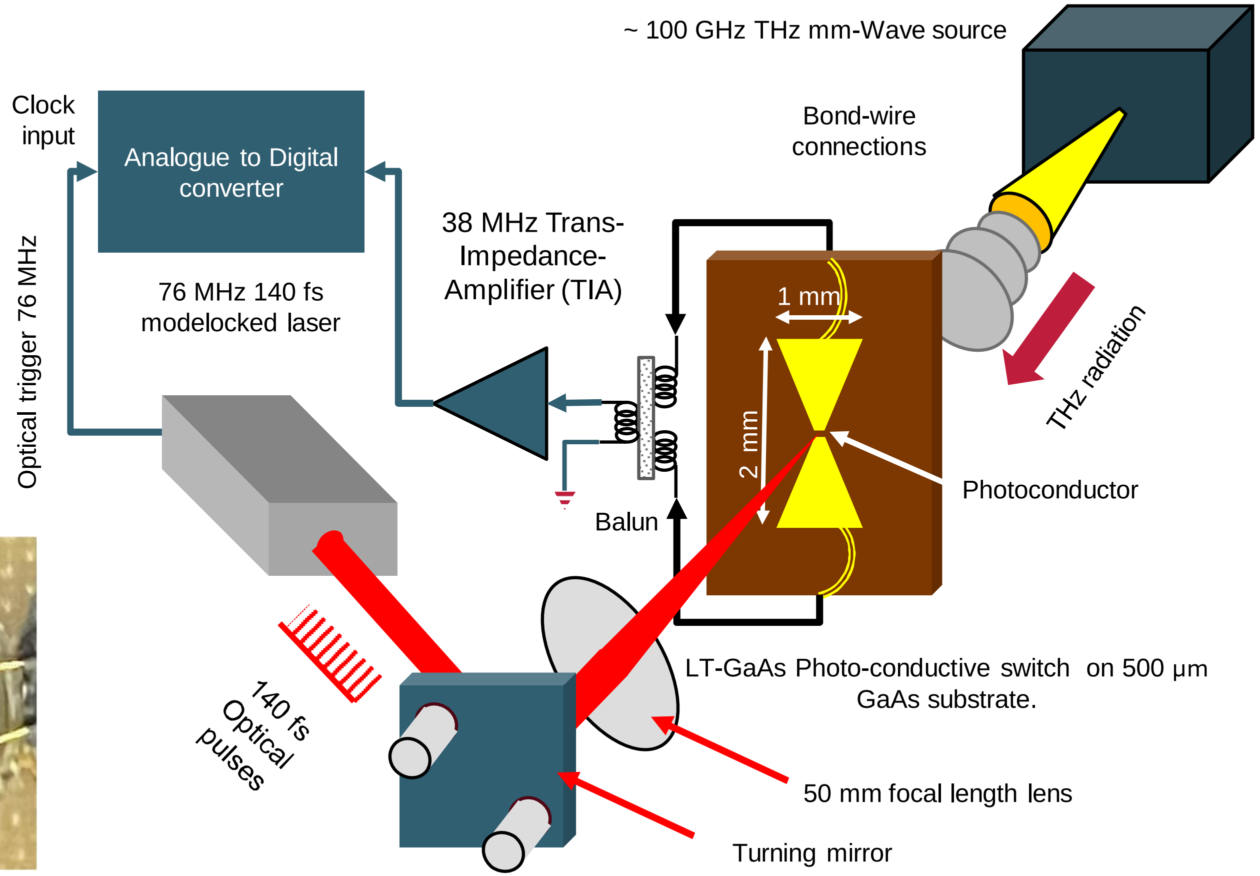


# Existing prototype – proof of principle

- LT-GaAs Photoconductor and Bow-Tie antenna available (P774)
- Six devices (1 mm x 2mm) on a single substrate
- Proof of principle/Evaluation of an existing prototype device [4]

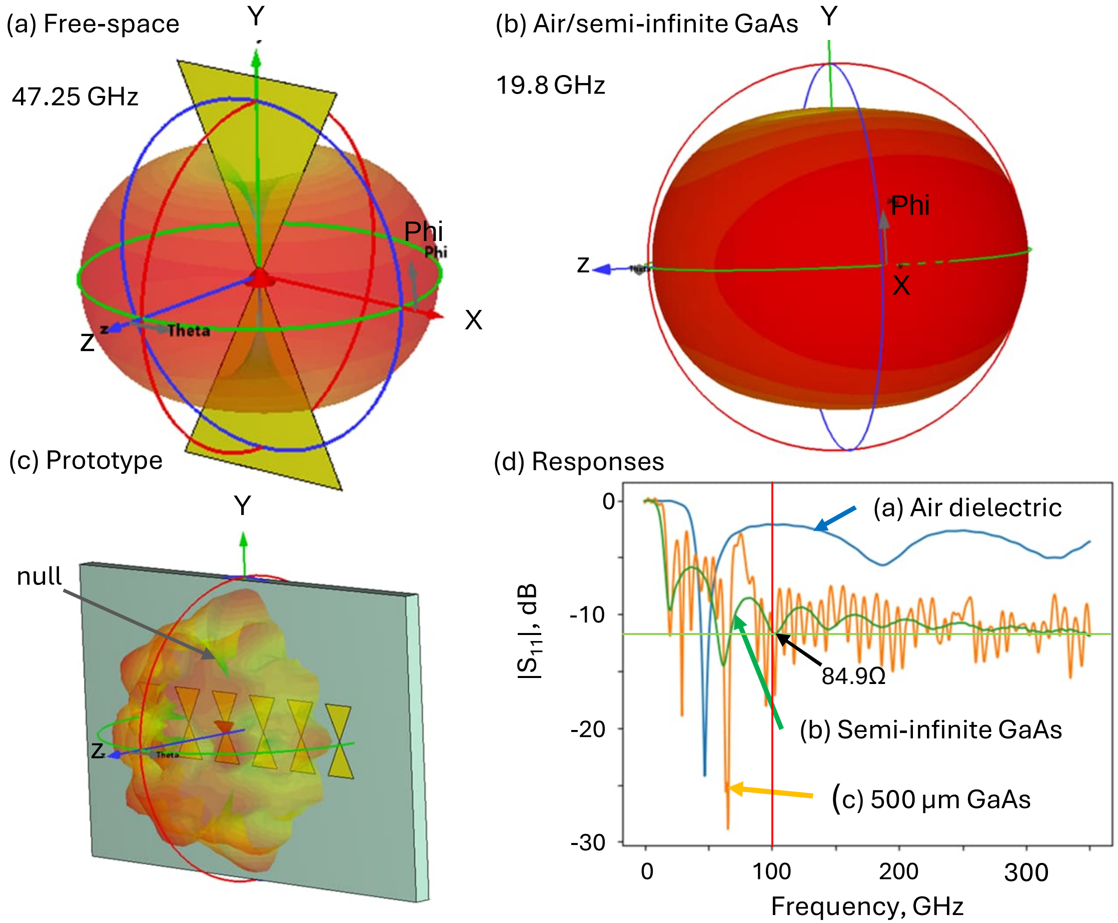




# Existing device modelling (P774)

- Impedance match $S_{11}$ ($Z_0$=50 Ω) modelled in CST for single and six devices on 500 µm GaAs substrate
- Antenna impedance from $S_{11}$ at resonant frequency
- Semi-infinite substrate approximations do not apply : Antenna (2 mm x 1 mm) and GaAs substrate (500µm) [4]
- (a) and (b) show the reduction in resonant frequency due to GaAs dielectric (see also (d))
- (c) shows a complex radiation pattern compared with (b). This is attributed to multiple modes and reflections at the substrate GaAs/air interface
- Prototype device operation at 100 GHz is a harmonic response. The antenna will support multiple modes
- An antenna needs to be much smaller for 100 GHz fundamental and 300 GHz harmonic operation
- Good impedance matching at the GaAs/air interface is essential. A thicker substrate may also help

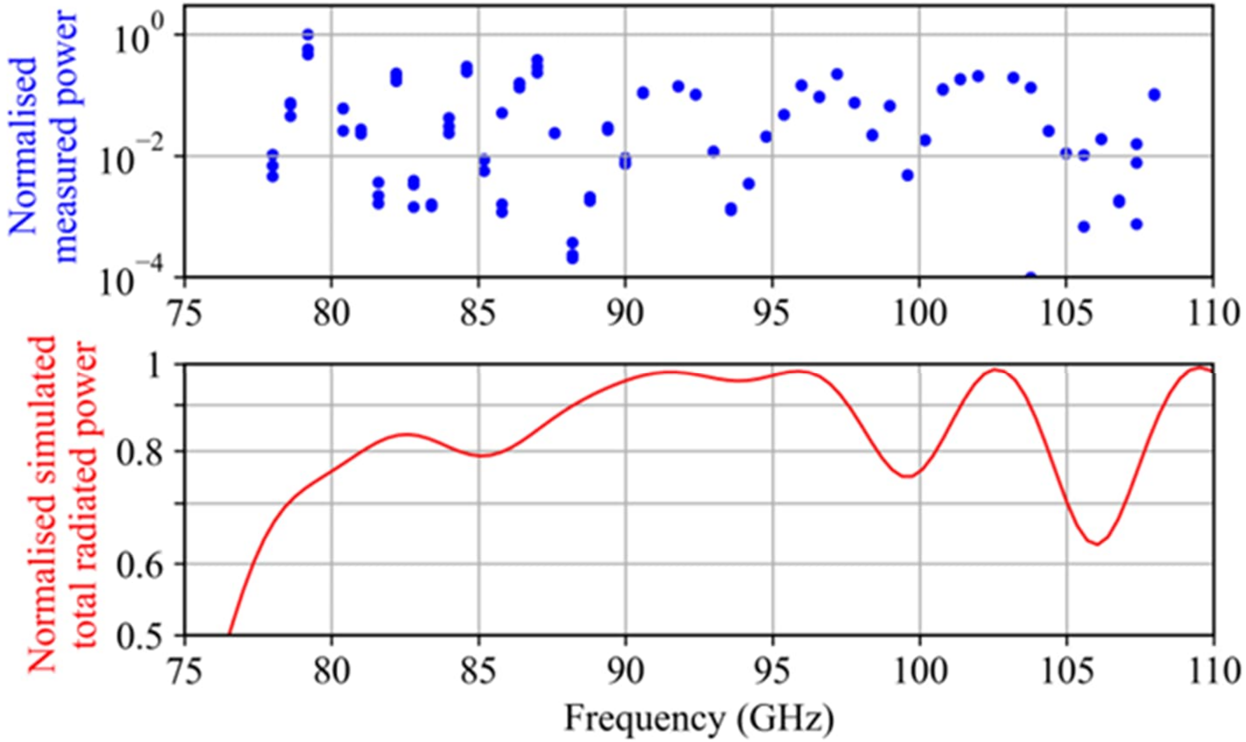





[4].H. Füser, "Terahertz frequency combs and terahertz steering," Ph.D. dissertation, Technische Universität Braunschweig, 2014.

# Measurement and modelling results for (P774) device

- Power scales are very different
- The upper plot shows measurements of CW power vs. frequency; the RF beam is divergent and not focussed
- The lower plot shows a simulation of the total radiated power vs. frequency. In this plot, the variations are much lower, suggesting that the overall radiation pattern is frequency dependent.
- Normalised radiated power proportional to $1-|S_{11}|^2$
- Measured power excursions >30 dB
- Possible radiated pattern variation

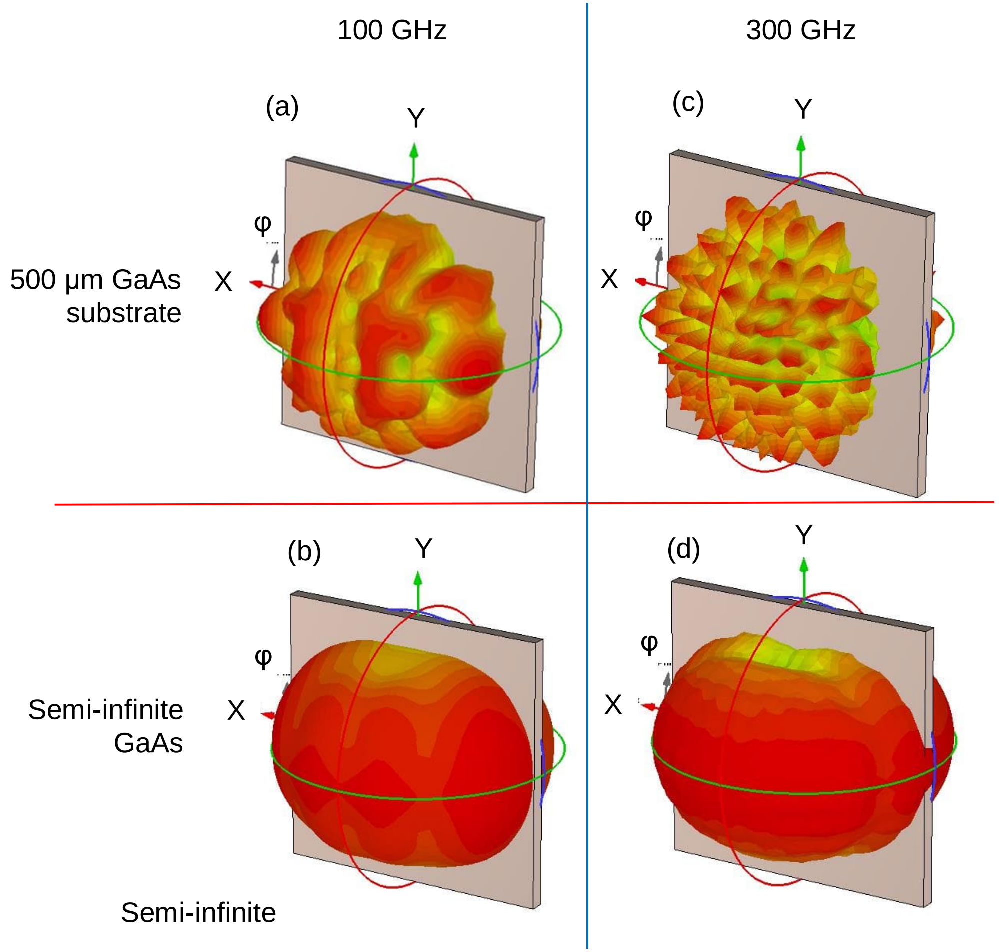


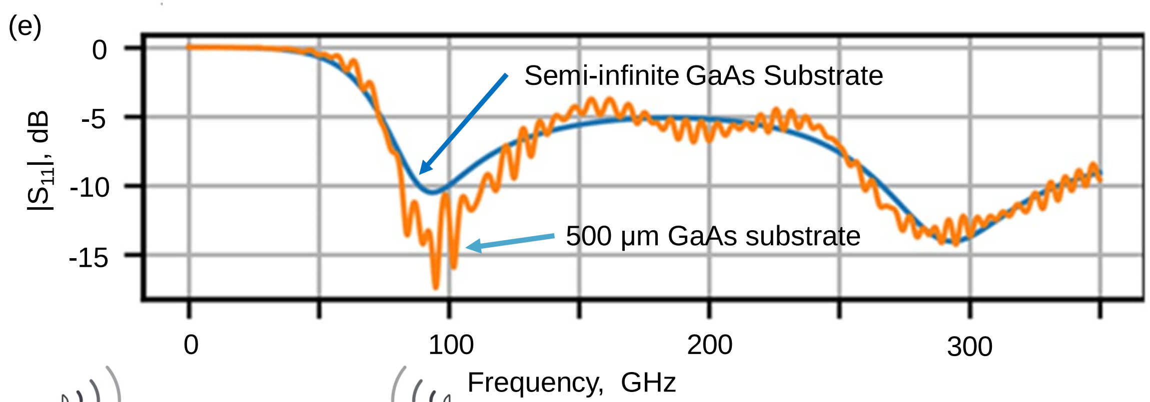



[4].H. Füser, "Terahertz frequency combs and terahertz steering," Ph.D. dissertation, Technische Universität Braunschweig, 2014.

# Revised device design

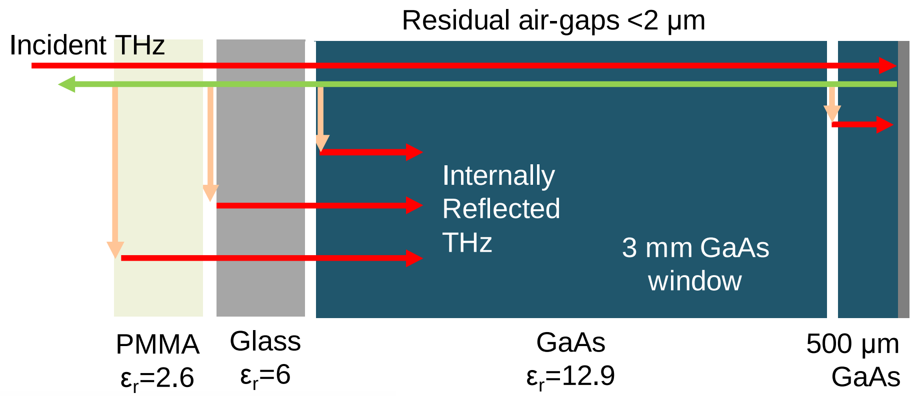
- Modelled antenna 450 µm long x 150 µm wide 10 µm x 10 µm gap
- Semi-infinite GaAs (b & d) or 500 µm (a & c) GaAs substrate
- No connections modelled (too small to wire-bond)
- Antenna on semi-infinite GaAs shows smooth antenna pattern
- $|S_{11}|^2$ response corresponds to total radiated and absorbed power (e)

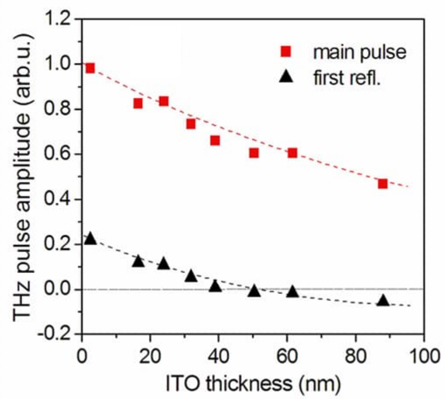


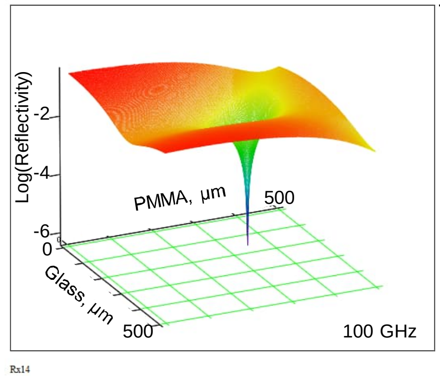
# Approximation for semi-infinite GaAs device

- Approximation to semi-infinite device is required
- Thick substrate >> antenna dimensions (unconstrained E-fields)
- Minimise reflection from the first Air/GaAs interface to minimise Etalon reflections
- Small antenna will require less substrate material, but the THz radiation may need to be focussed
- $\varepsilon_r$ of suitable THz materials to minimise reflections Fresnel calculations (narrow-band solution). THz matching layer thickness much higher than optical equivalent [5-6]
- Thin metal layer approach may offer a broadband response. 44nm Indium Tin Oxide  on GaAs minimises reflection over 400 GHz – 4.5 THz [7]
- A two-part solution is proposed: polished Antenna/substrate (500 µm) and GaAs window (3-4 mm) with matching material layers/coating. Different matching/coating layers can be evaluated with the same device




510 µm thick gallium-arsenide with an indium tin-oxide film. (lines – simulation) from [1]



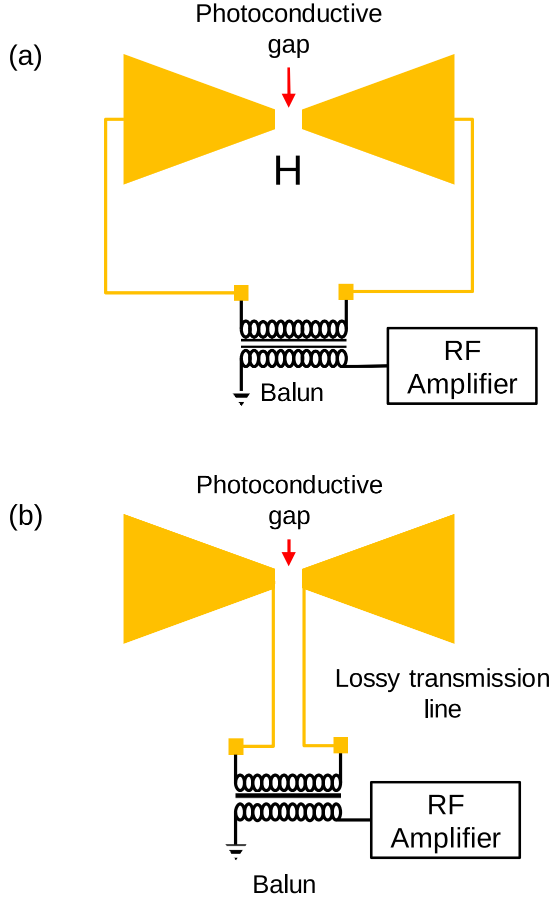

Internal reflection from the back GaAs interface. Single layer (465 µm PMMA) gives $E_{reflect}$ 16% at 100, 300 GHz. Dual layer (184 µm glass, 339 µm PMMA) gives $E_{reflect}$ 0.074% at 100 GHz.



[5] Zhai, M., et al., “Terahertz Dielectric Characterization of Low-Loss Thermoplastics for 6G Applications,” Int J Wireless Inf Networks 29, 269–274 (2022).
[6] Hirata, A. et al., "Measurement of Glass Complex Permittivity at 200-500 GHz for THz Propagation Simulation," 2020 Int. Symp. on Ant. and Propag. (ISAP), Osaka, Japan, 2021,
[7] Kröll J, Darmo J, Unterrainer K. Metallic wave-impedance matching layers for broadband terahertz optical systems. Opt Express. 2007 May 28;15(11):6552-60.

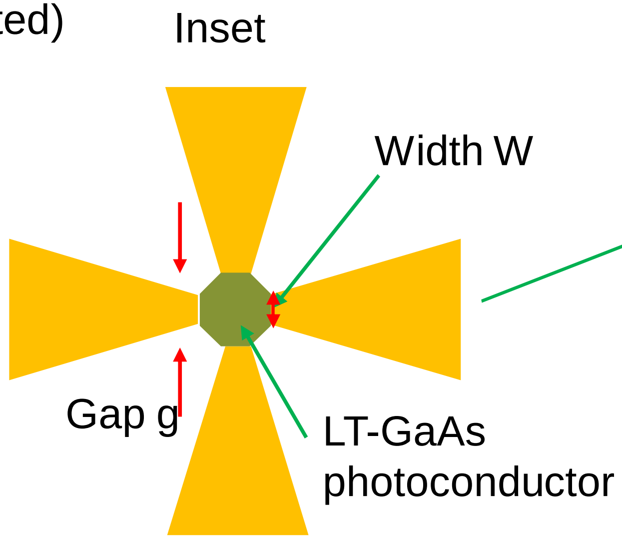
# DC/RF Connection options

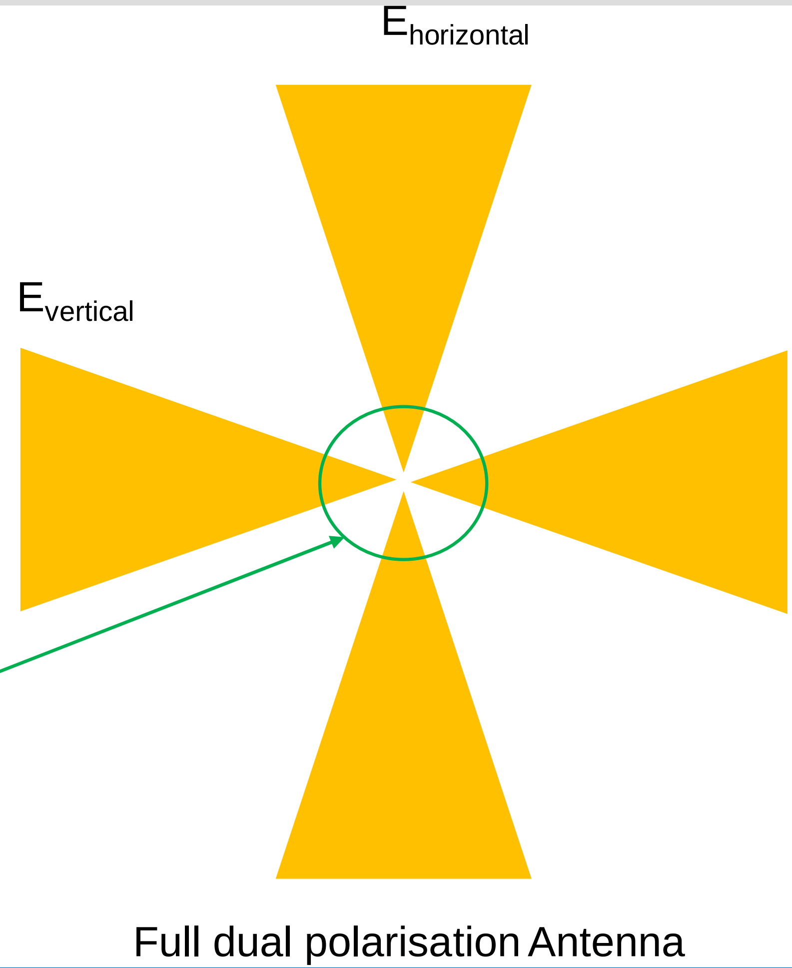
- Small device (450 µm long for 100 GHz) Bondwire solution is impractical
- Mixing device so RF signal not used – loading the RF signal reduces sensitivity
- (a) thin (inductive) lines connected to the ends of the antenna elements – large H antenna loop, may affect the antenna characteristics
- (b) Transmission line connection – negligible H antenna loop, may load the antenna at THz RF frequency
- Lines and gaps limited to about 10 µm (dust etc)
- Similar mapping to coplanar line geometry
- Impedance may be tailored to optimise Z(f) at selected frequencies.
- 2nd prototype device 450 µm long x 150 µm wide
  10 µm x 10 µm gap fabricated



# Dual polarisation Photoconductive device proposal

- The photoconductor is not restricted to operating in a single direction, so the RF radiation could contain both horizontal and vertical polarisation components.
- Photoconductive excitation is synchronous for both polarisation-states. The result is a superposition, and the carriers move under combined electric field
- Bow-Tie antennas have a degree of cross-polarisation sensitivity (which can be calibrated)
- Critical optical alignment



# Summary

- Summary of guided-wave and free-space options for Traceability of modulated waveforms
- Evaluated and modelled an existing prototype Bow-Tie photoconductive antenna device
- Demonstrated Proof of principle with CW THz
- Modelling shows response-flatness problems linked to reflection from a finite substrate thickness
- Narrowband and broadband compensation for reflections from the substrate/air interface
- DC/IF connection strategies
- Outlined strategy for a dual polarisation device
- See Posters (workshop and conference) for further details
- Outstanding tasks
- Prototype device fabricated. Testing in progress
- Test demountable Reflection mitigation strategies (CW)
- Measurements of modulated (nQAM or QPSK) waveforms

# References


1. BIPM, "VIM: International Vocabulary of Metrology - basic and general concepts and associated terms (2012)," Available at: https://doi.org/10.59161/JCGM200-2012

2. A. Schramm, F. Gellersen, F. Rausche and K. Kuhlmann, "Traceable S-Parameter Measurements Up to 165 GHz Using 0.8 mm Coaxial Standards," in IEEE Microwave and Wireless Technology Letters, vol. 35, no. 6, pp. 936-939, June 2025, doi: 10.1109/LMWT.2025.3562419.

3. J. Dunsmore, “A new calibration method for mixer delay measurements that requires no calibration mixer,” in 2011 41st European Microwave Conference, 2011, pp. 480–483.

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# Thank you very much for your Attention

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