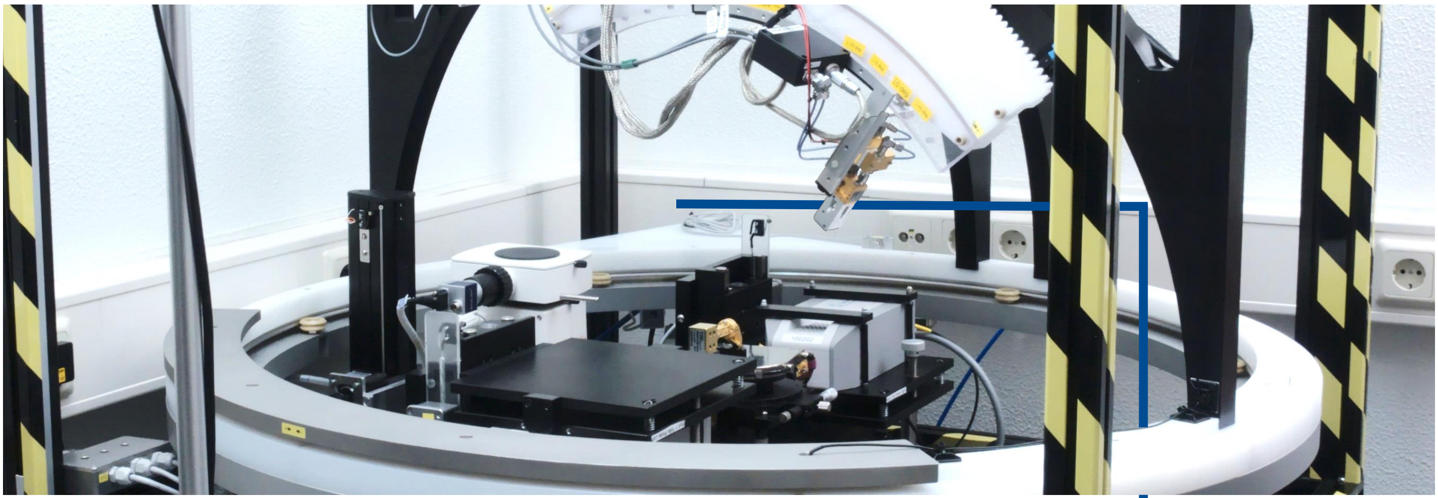

Understanding planar mm-wave antennas

From modeling to measurements

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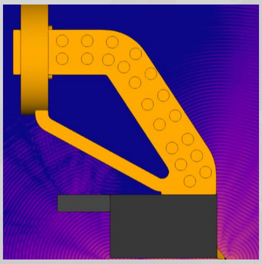
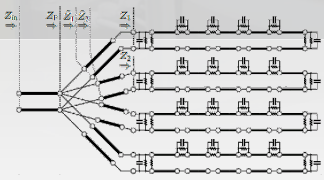
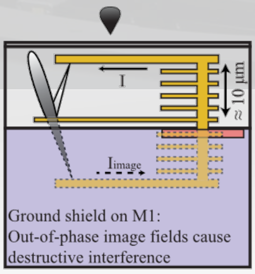
Contents

- Motivation – *understanding* antennas
- Simple and (not too) complex antenna models
- Practical examples







- Measurement – *prove* your understanding
- On wafer probes
- Measurement setups

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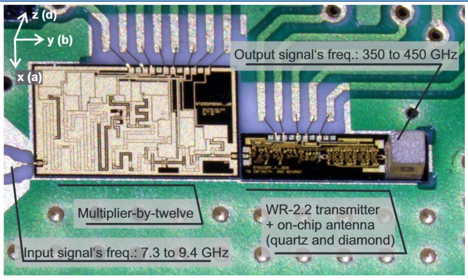
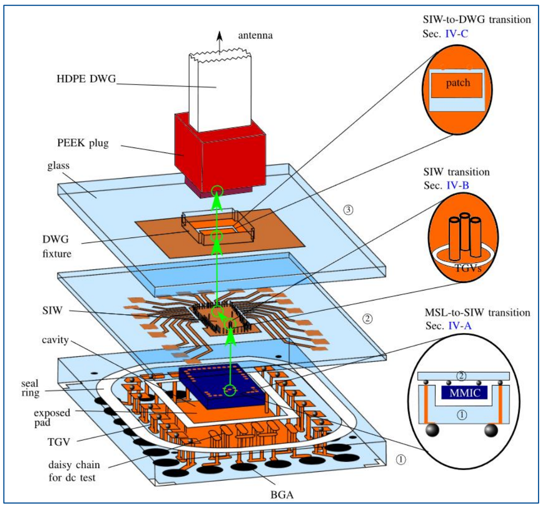
(Why) is antenna design still a thing?

- You'll find solutions to all your (antenna) problems in a textbook
- On-chip environment contradicts typical design requirements
  - ➢ Limited DOF in layer-stack
  - ➢ Moderate/Large dielectric constants
  - ➢ Challenging micromachining
- Typical tradeoff between complexity and performance



B. Gashi *et al.*, "Broadband 400 GHz On-Chip Antenna with a Metastructured Ground Plane and Dielectric Resonator," *IEEE Trans. Ant. Propag.*, Early Access, 30th May 2022, DOI: 10.1109/ TAP.2022.3177527



T. Galler *et al.*, "Glass Package for Radar MMICs Above 150 GHz," *IEEE J. Microw.*, vol. 2, no. 1, pp. 97–107, Jan. 2022

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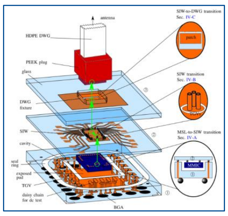
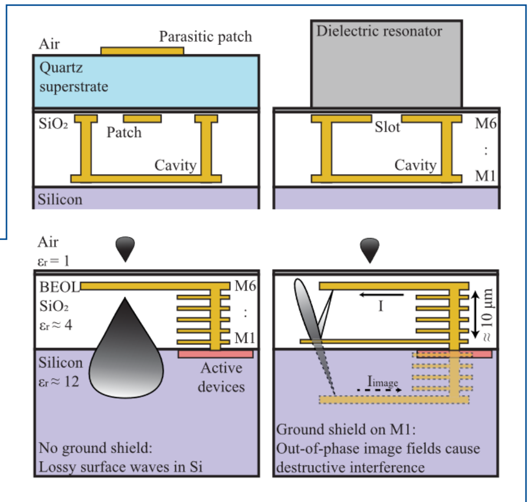
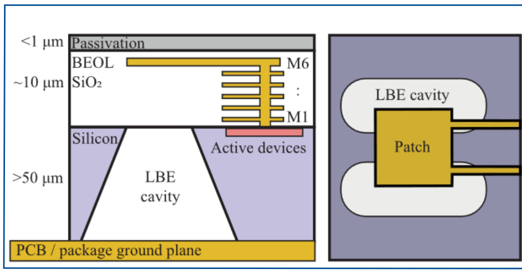
On Chip Antenna Challenges

- LTCC or glass wafer as off-chip solutions
- On-Chip solutions suffer either from
  - ➢ Low ground distance (limited efficiency)
  - ➢ Large dielectric thickness (substrate waves)
- Large dielectric lenses scale directivity/gain



T. Galler *et al.*, "Glass Package for Radar MMICs Above 150 GHz," *IEEE J. Microw.*, vol. 2, no. 1, pp. 97–107, Jan. 2022



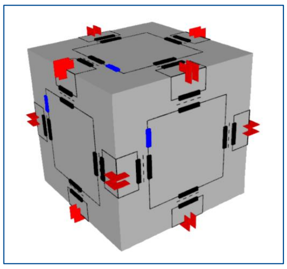


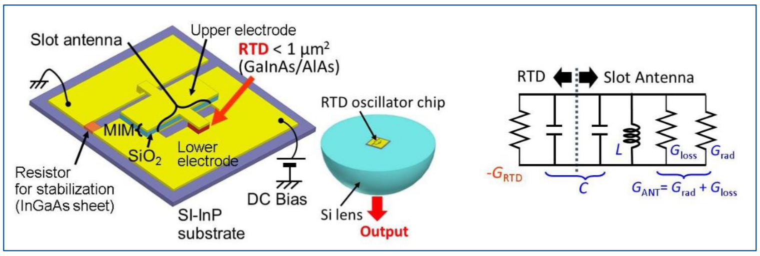
M. de Kok, A. B. Smolders, and U. Johannsen, "A Review of Design and Integration Technologies for D-Band Antennas," *IEEE Open J. Ant. Propag.*, vol. 2, pp. 746–758, 2021

Modeling Antennas using Equivalent Circuits

- Equivalent circuits (EC) represent selected antenna properties through an electrical network
- Finding an EC is additional effort
- ECs do not capture all antenna properties
- Simplicity is key, the most general (and most complex) representation is found in full wave time-domain solvers (EC-Finite Difference Time Domain)

Rennings, A., "Elektromagnetische Zeitbereichssimulationen innovativer Antennen auf Basis von Metamaterialien," Ph.D. dissertation, ATE, University of Duisburg-Essen, Duisburg, Germany, 2008.



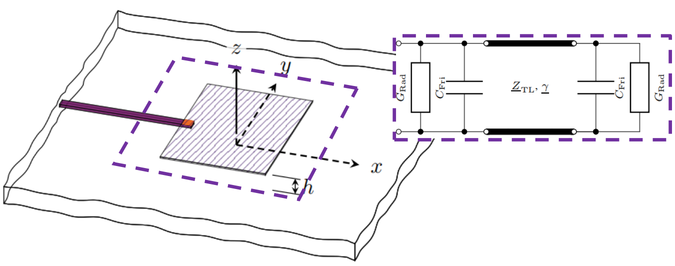


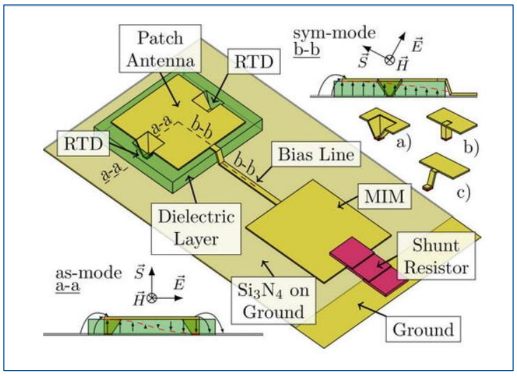
M. Asada and S. Suzuki, "Terahertz Emitter Using Resonant-Tunneling Diode and Applications," *Sensors*, vol. 21, no. 4, 1384, Jan. 2021

- Fundamental description of antenna operation (shunt/series resonance, DC-behavior,…)
- Physical insight into antenna operation
  - Attribute antenna geometry to EC (or vice versa)
  - Tuning towards desired operation in *circuit perspective*
- More efficient transient/harmonic balance simulations to investigate antenna/device Coupling

Patch Antenna – Impedance, Coupling, Radiation

- Microstrip Patch radiates through end conductances G_{Rad}
- Length is determined by fringing capacitance C_{Fri}



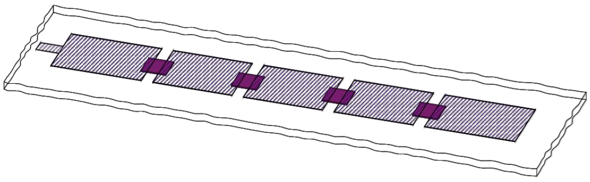


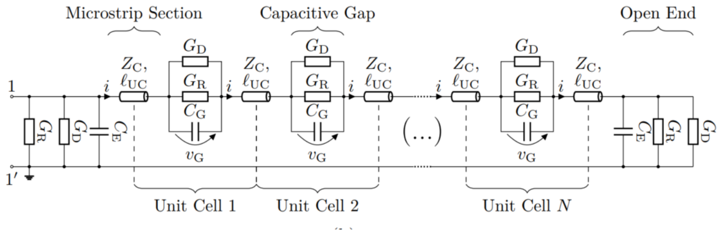
P. Ourednik and M. Feiginov, "Double-resonant-tunneling-diode bridge-less patch-antenna oscillators operating up to 1.09 THz," *Appl. Phys. Lett.*, vol. 120, no. 18, p. 183501, May 2022

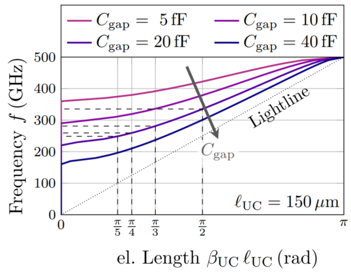
- Coupling is easily estimated analytically (cf. A. Derneryd, "A theoretical investigation of the rectangular microstrip antenna element," *IEEE TAP*, vol. 26, no. 4, pp. 532–535, Jul. 1978)
- Fractional bandwidth is proportional to substrate height, efficiency is limited

Cap. Enhanced Patch Antenna I

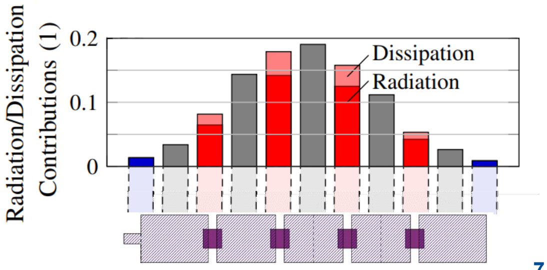
- Enable additional radiation conductances by adding capacitive discontinuities in series





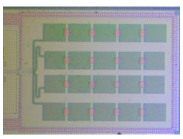


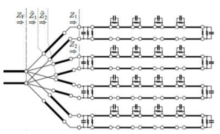
- Negative phase shift due to capacitances is compensated by longer antenna
- Increasing capacitances decrease bandwidth
- Each capacitance enables significant radiation

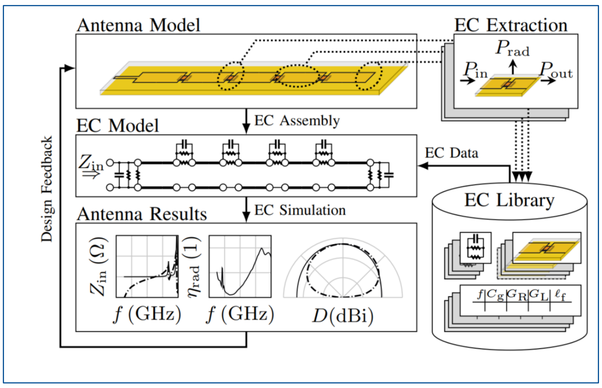


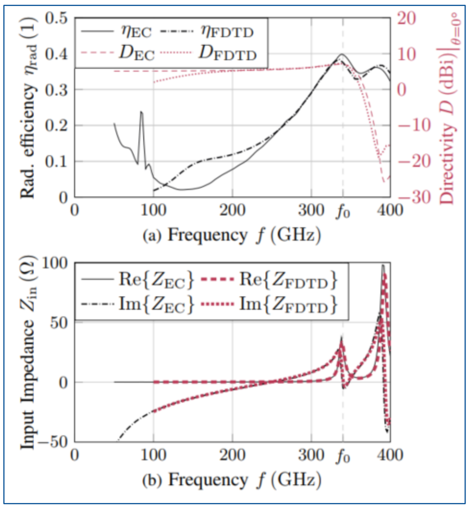
Cap. Enhanced Patch Antenna II

- Radiation and Dissipation are separated in EC and allow for
  - Input impedance, efficiency, directivity,.. estimation
- Cf. PEEC: A. E. Ruehli, "Equivalent Circuit Models for Three-Dimensional Multiconductor Systems," *IEEE Trans. Microw. Theory Tech*, vol. 22, no. 3, pp. 216–221, Mar. 1974







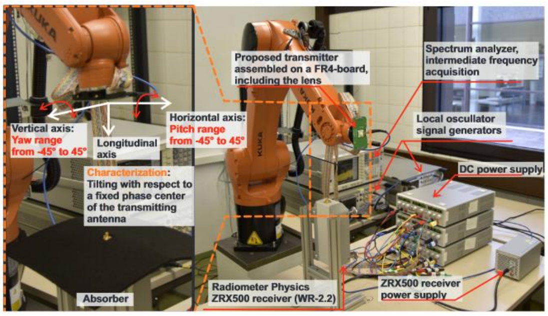


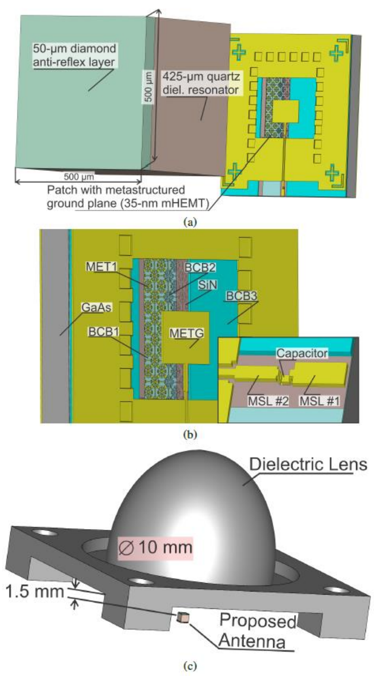
B. Sievert, J. T. Svejda, J. Wittemeier, N. Pohl, D. Erni, and A. Rennings, "Equivalent circuit model separating dissipative and radiative losses for the systematic design of efficient microstrip-based on-chip antennas," *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 2, pp. 1282–1294, Feb. 2021

Practical Examples

Metasurface Enhanced Patch

- 100 GHz (25%) operation bandwidth of the antenna
- Metasurface below patch to mitigate ground-plane efficiency degradation
- Metasurface bandwidth requires substrate height of 50um
- Dielectric resonator to achieve permittivity matching and stabilize radiation pattern





B. Gashi *et al.*, "Broadband 400 GHz On-Chip Antenna with a Metastructured Ground Plane and Dielectric Resonator," *IEEE Trans. Ant. Propag.*, Early Access, 30th May 2022, DOI: 10.1109/TAP.2022.3177527

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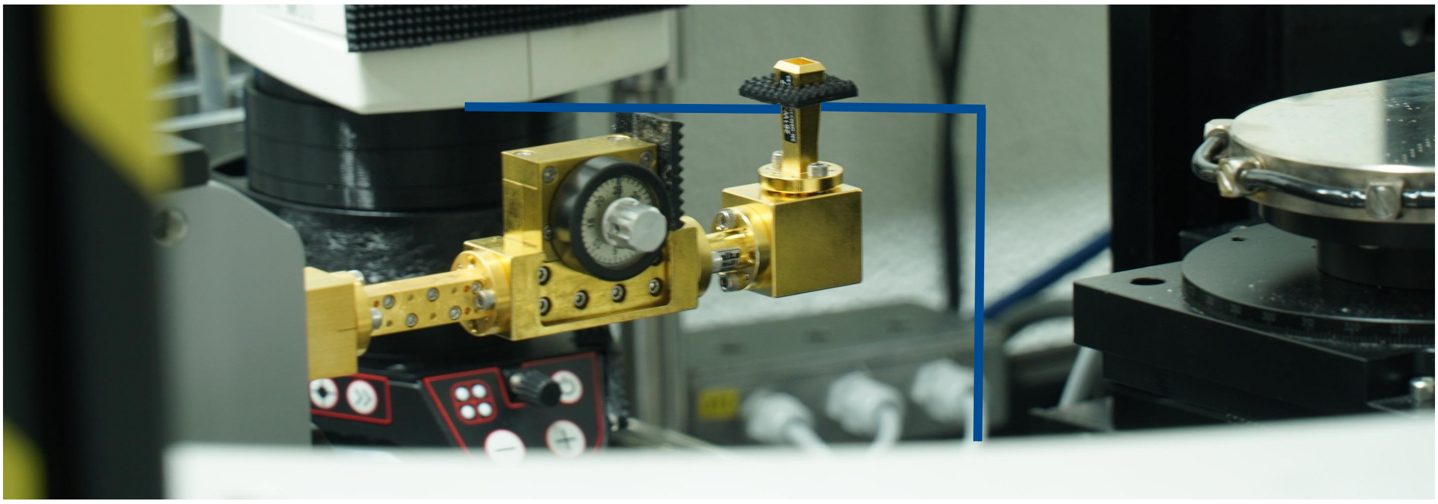

mm-Wave Antenna Measurements

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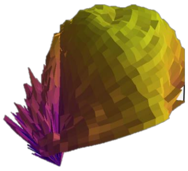
Challenges in mm-wave (Antenna) measurements

Low directivity/small antennas

- Probe radiation might interfere with antenna radiation
- Far field condition is easily achieved
- Near field measurements are seldom carried out



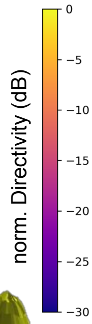
- All measurement points are of similar amplitude
  - ➢ Scattering at probe is highly relevant

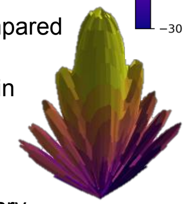
Far field definition(s):

"IEEE Recommended Practice for Antenna Measurements," IEEE Std 149-2021 (Revision of IEEE Std 149-1977), pp 1-207, Feb. 2022, doi: 10.1109/IEEESTD.2022.9714428.

High directivity/large antennas

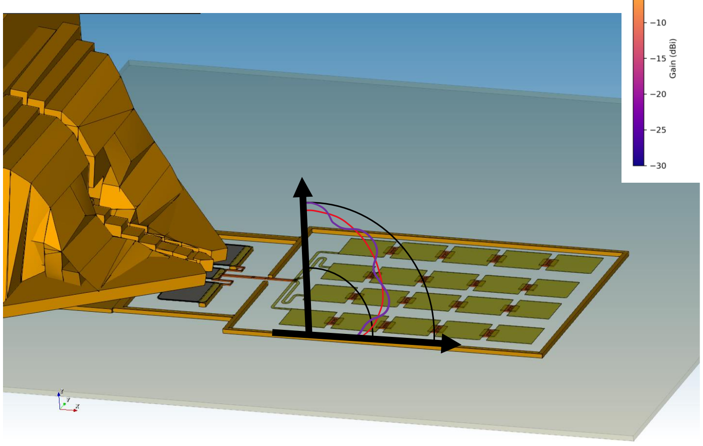
- Probe radiation practically irrelevant
- Sufficient measurement distance necessary
- If far field cannot be achieved, near field measurement might be an alternative
- Main beam is orders of magnitudes larger compared to nulls/sidelobes
  - ➢ Scattering at the probe is irrelevant for main beam
  - ➢ Any main-beam reflection disturbs other measurement points (far field)
  - ➢ Comparably larger dynamic range necessary

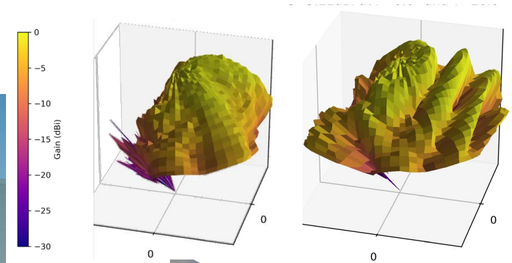


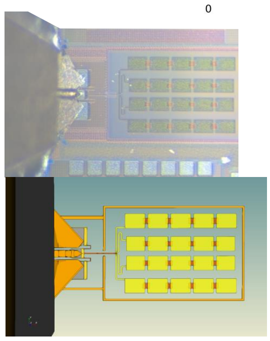


Probe Influence I

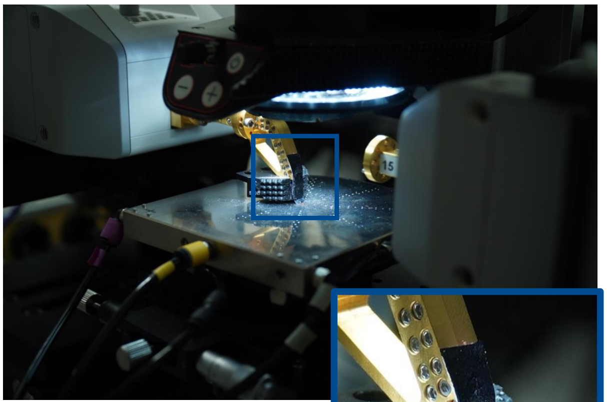
- The probe is huge with respect to the antenna size
- The tip is in the very near-field
- The body is at least in far-field
- Superposition (*array*) of original and image antenna



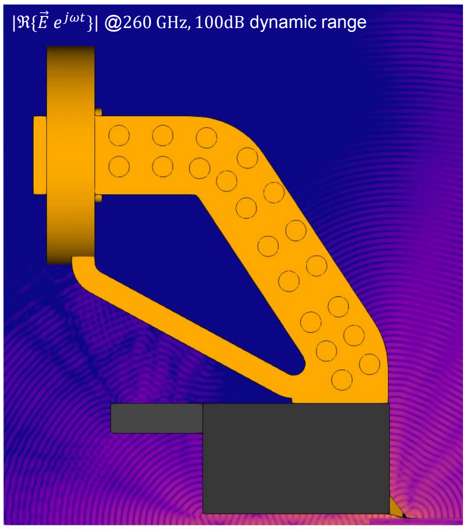




Probe Influence III



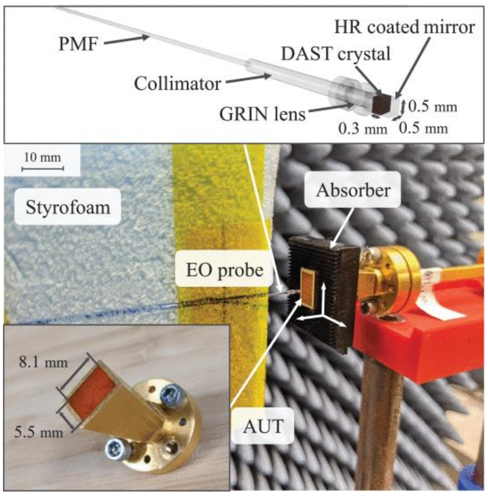
- One could increase the feed length
- Time-Gating is barely possible (BW~100GHz)
- Cover probe body (and tip) in absorbers
- Large shadow region
  - ➢ Especially bad for LWA backside radiation
- Probe radiates itself, even for *matched* load
- Probe cannot be considered an excellent match



Near-Field Measurement

- Typically, only Co-Pol is measured
- Near2Farfield Transform
  - ➢ Typ. with Phase Measurement
  - ➢ Sampling Setup, e.g. Cartesian or other COS
  - ➢ Calculate 3D Pattern
- Especially suitable for large antennas (no far-field)
- Directivity (full 3D-Pattern) and Gain (Reference Antenna) enables efficiency calculation
- Near field is measured w. dielectric/rectangular waveguide or mixing receivers
- Impractical for probe-fed topside-radiating antennas

VNA & Rect. WG-Based: A. Jam and K. Sarabandi, "A Submillimeter-Wave Near-Field Measurement Setup for On-Wafer Pattern and Gain Characterization of Antennas and Arrays," *IEEE Transactions on Instrumentation and Measurement*, vol. 66, no. 4, pp. 802–811, Apr. 2017

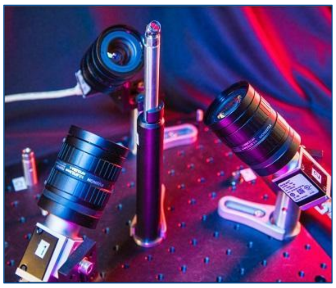


Y. Tanaka et al., "Photonics-Based Near-Field Measurement and Far-Field Characterization for 300-GHz Band Antenna Testing," IEEE Open Journal of Antennas and Propagation, vol. 3, pp. 24–31, 2022

Measurement Setups

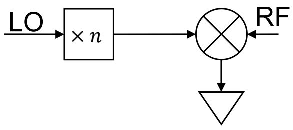
Near-Field/Far-Field Measurement

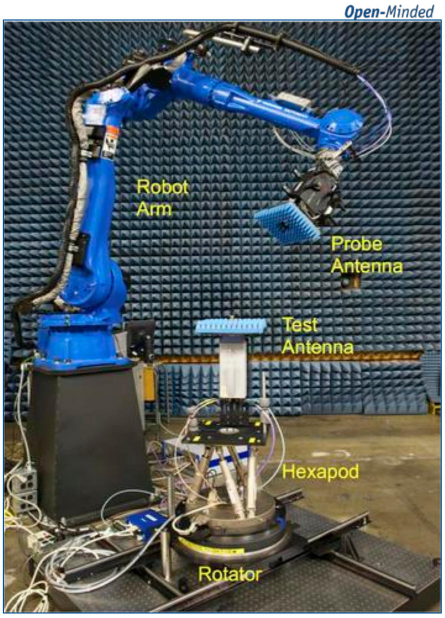
- Phase-stable measurements w. high position accuracy
- Position feedback (self-developed laser tracker)
- Especially suitable for large antennas
- Waveguide fed antennas only



National Institute of Standards and Technology
https://www.nist.gov/ctl/single-pixel-touchless-laser-tracker-probe-pixel-probe

- 25um accuracy by tracking
- Cable movement/phase stability:
  D. R. Novotny, “Reducing Effects of LO Cable Movement in Antenna and Long Distance VNA Measurements,” in *2019 Joint Int. Symp. EMC & EMC Sapporo/APEMC*, Jun. 2019, pp. 585–588.



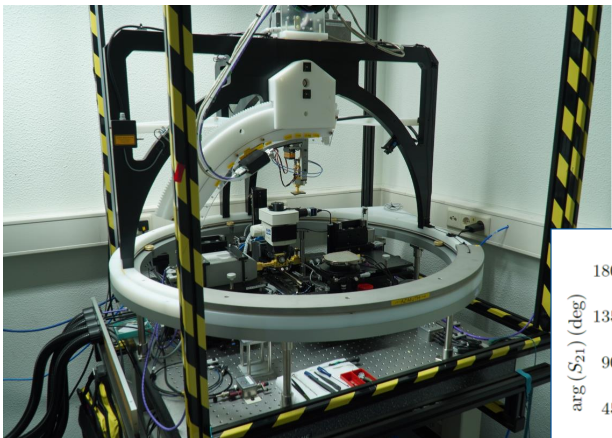


National Institute of Standards and Technology
https://www.nist.gov/ctl/configurable-robotic-millimeter-wave-antenna-cromma

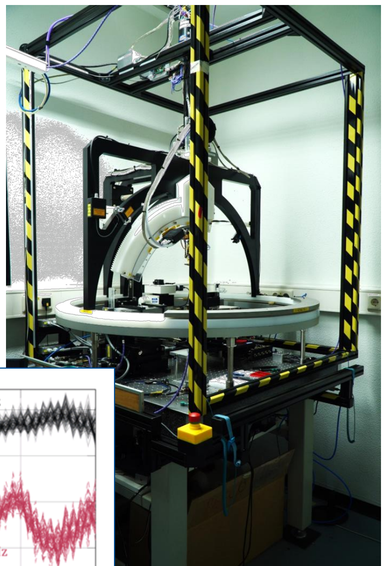
Measurement Setups

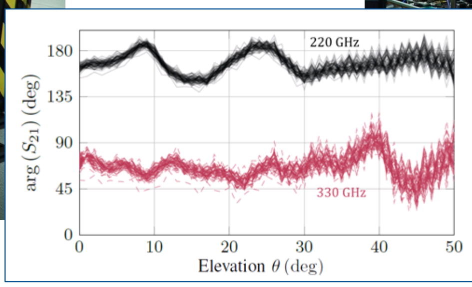
Wafer Antenna Measurement System

- Inherently spherical coordinates (Position&Polarization)
- VNA-based characterization



- Two xyz-stages for on-wafer probes /near field probes/…
- Rotary joint for azimuth rotation, phase-stable cables

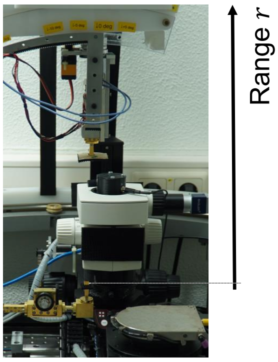


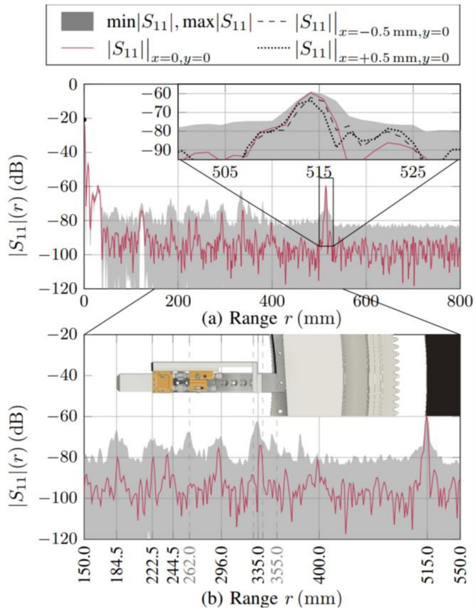


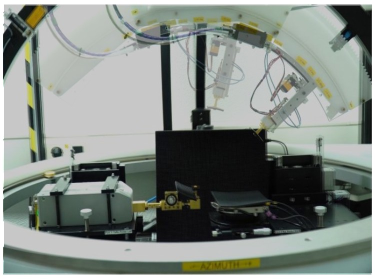
Measurement Setups

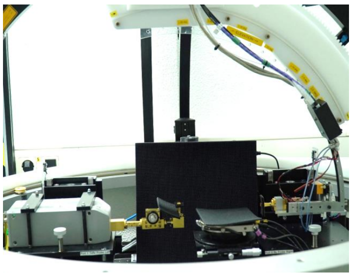
Coordinate System

- Azimuth rotation enabled by rotary joint
  - ➢ repeatable phase deviation
- Elevation limited to 55°
  - ➢ Mechanically guided, phase stable cable
- Phase error dominated by mechanics





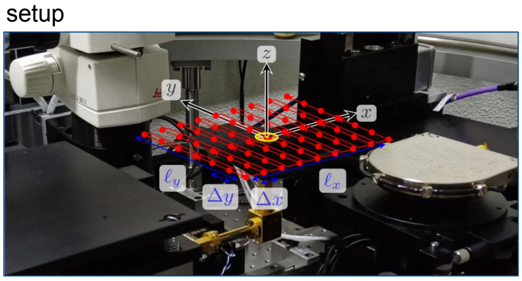




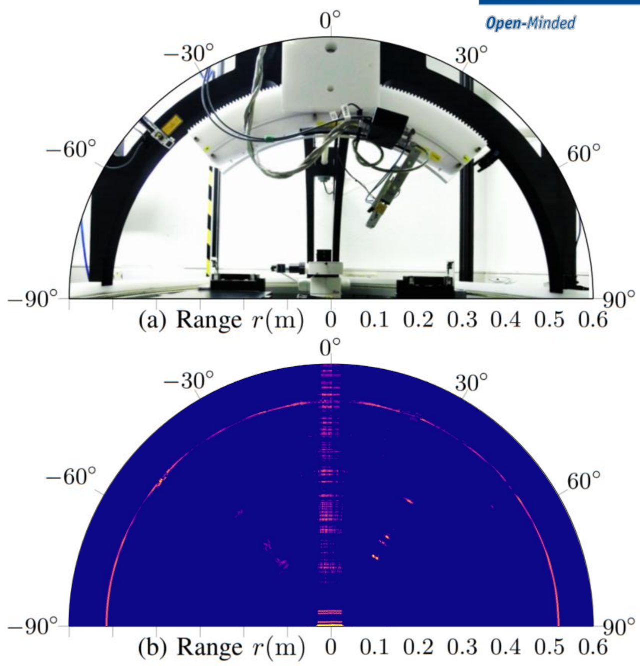
Measurement Setups

SAR Self Characterization

- Open-ended waveguide as SAR Tx/Rx-antenna
- Measure input reflection at 101x101 sampling points in x-y-plane
- Backprojection into x-z plane (others are possible as well) to identify reflections inside the measurement setup

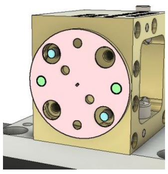


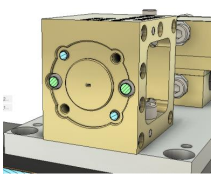
B. Sievert, J. T. Svejda, D. Erni, and A. Rennings, "Spherical mm-Wave/THz antenna measurement system," *IEEE Access*, vol. 8, pp. 89680–89691, 2020

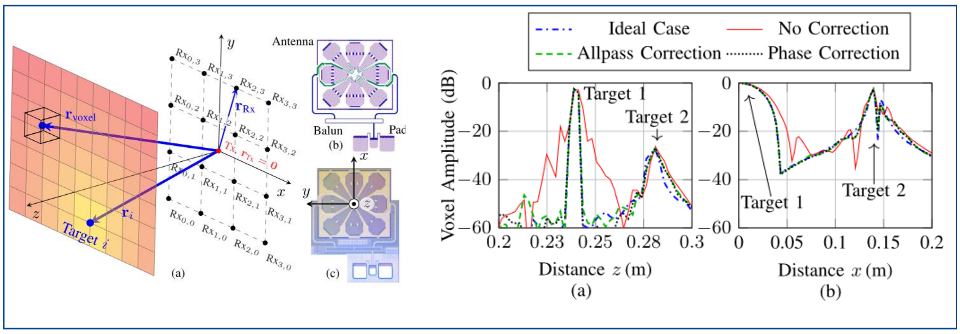


Circular Polarization Measurement

- CP Reference Antenna
- Trace ellipsoidal amplitude
- Phase stable measurement of E_φ, E_θ
  - Good radial accuracy in farfield
  - No offset by polarization switch
  - No phase drift
  - Rotate the Rx waveguide:

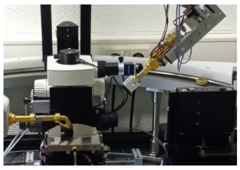






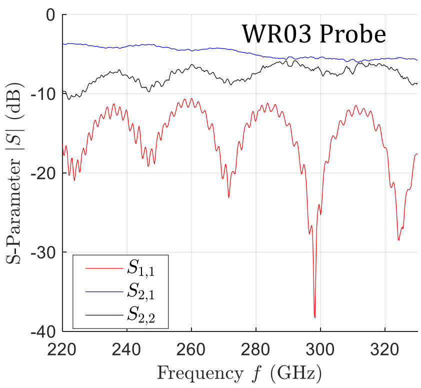
J. Wittemeier, B. Sievert, M. Dedic, D. Erni, A. Rennings, and N. Pohl, “The Impact of Group Delay Dispersion on Radar Imaging With Multiresonant Antennas,” IEEE Microw. Wirel. Comp. L., vol. 32, no. 3, pp. 241–244, Mar. 2022

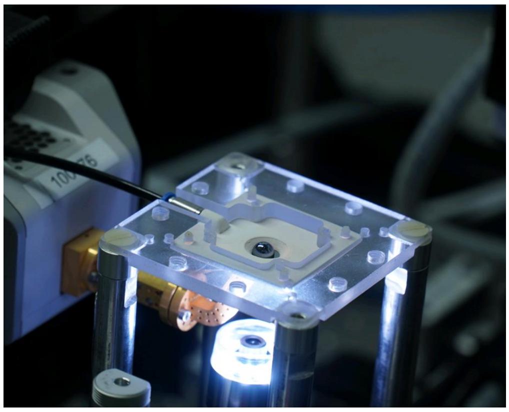
- Performed a phase-correct radiation measurement of a CP antenna
  - Group delay as measure for antenna dispersion
  - Simulated effect of group delay on radar imaging
- Measurement of group-delay is an overkill compared to the self-characterization of an exsiting radar

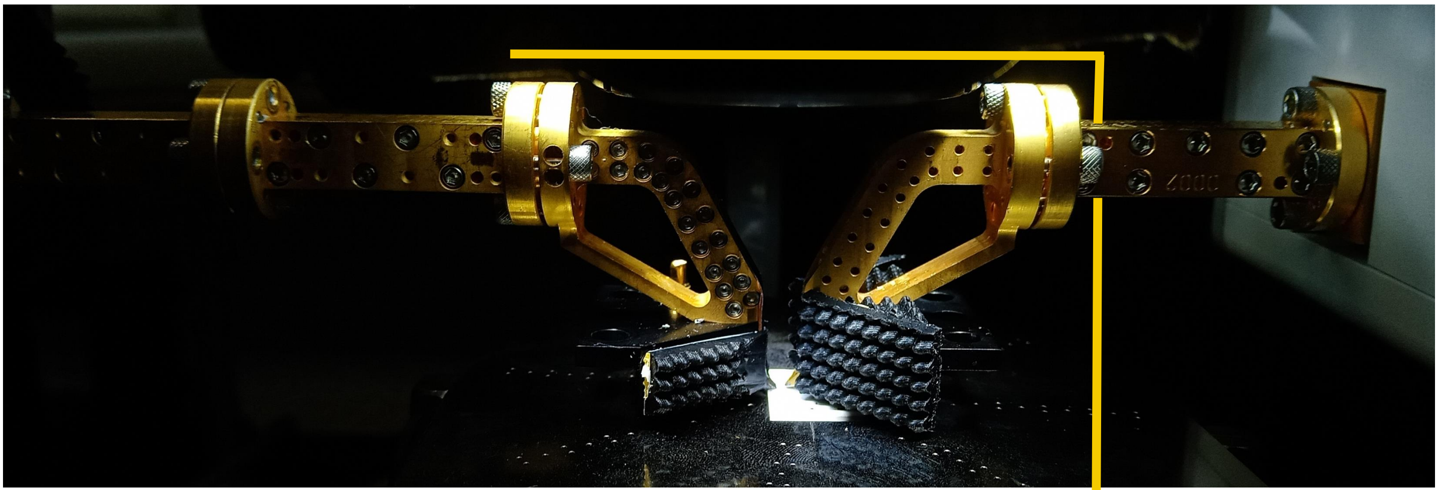


Things which have not been mentioned

- Temperature drift is an severe effect
  - Perform interdependent measurements in close succession (e.g. E_φ and E_θ-Pol for CP)
- Phase error sources
  - Temperature
  - Cable flex
  - Mechanics
- Probes are not matched, not identical
- Characterize your own probe using OSM
- Consider own calibration standards on chip
- Characterize full systems







Thank you for your attention!

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Thanks to: J. T. Svejda, A. Rennings, D. Erni, and the ATE (UDE), Insys (RUB), TRR MARIE.

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IWMTS

INTERNATIONAL WORKSHOP ON MOBILE THZ SYSTEMS

2022 Fifth International Workshop on Mobile Terahertz Systems (IWMTS), 4-6 July 2022

*****Paper submission deadline extended until March 21!*****

The 2022 Fifth International Workshop on Mobile Terahertz Systems (IWMTS) will be held in Duisburg, Germany, and online as hybrid workshop on 4-6 July 2022. The exact workshop venue will be announced in due time.

IWMTS sets itself apart from well-known THz conferences by focusing on "Mobile THz Technology and corresponding THz Systems" since the organizing committee believes that “Mobility" will ultimately push THz solutions to mass markets. Of course, progress reports on traditional technological advances for THz components and theoretical studies on THz wave propagation as well as related topics are also highly welcome.

Topics of the workshop include (though are not limited to) the following areas focusing on THz frequencies and mobility:

- Devices and systems
- Antennas and propagation
- Measurements, simulations and modeling
- Electronic and photonic transceivers
- Prototypes and testbeds
- Material characterization
- Spectroscopy
- Signal processing
- Communications (in particular 6G)
- Localization
- Identification
- Imaging and remote sensing
- Beamforming and -management
- Data and sensor fusion
- Applications

Confirmed Keynote Speakers

- Andrea Markelz, Title: “Using Terahertz Microspectroscopy to Measure Biomolecular Dynamics”
- Ho-Jin Song, Title: “What do future THz Communications Systems perform: In Perspective of Implementation and Energy Efficiency”
- Chi-Hou Chan, Title: “Terahertz Antennas for 6G and Beyond - Design, Prototyping, and Characterization”
- Nikhil Ponon, Title: “Terahertz express analyser for rapid detection of SARS-CoV-2”

Special Sessions:

- Wireless Glucose Sensing (organized by Victor Pikov)
- THz Identification (organized by Frédéric Garet)

Tutorial:

- On-Chip Antennas (organized by Daniel Erni)

Apply for the IWMTS ”TalentTravel” Program

Travel grants are available in the new ”TalentTravel“ Program.
For more information please visit www.iwmts.org.
Application deadline: February 28, 2022

Join the panel session:
”Will Mobile THz Systems revolutionize Mobile Medical Diagnosis?”

Special Issue in IEEE Transactions on Microwave Theory and Techniques

Authors of all papers presented at IWMTS 2022 are invited to submit an extended version of their papers to a Mini-Special Issue of IEEE Transactions on Microwave Theory and Techniques. Every paper will be reviewed in the same manner as all other regular submissions. Further information can be found on www.iwmts.org.

Important Dates

Full Paper Submission Deadline:
March 21, 2022

Proposal for Special Sessions:
February 28, 2022

Acceptance Notification:
April 18, 2022

Camera-ready Submission:
May 16, 2022

IWMTS Organizing Committee

General Chair	**Thomas Kaiser**
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Papers are invited to be uploaded on the EDAS system: https://edas.info/newPaper.php?c=28804. The manuscript should follow IEEE two column format with single spaced, 10 pt font in the text. MS or LaTex templates can be downloaded from https://www.ieee.org/conferences/publishing/templates.html. The manuscript length should be three to five pages, including all figures, tables, references, and so on. All papers which meet IEEE quality standards and presented by one of the authors will be submitted to IEEE Xplore for indexing. More details about the workshop can be found on www.iwmts.org.