Technology

The path towards 6G – technology concepts

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ROHDE&SCHWARZ

Make ideas real

The path towards 6G

- B5G and 6G research areas
- Properties and applications of THz waves
- THz generation by electronic and photonic technologies
- Optical wireless communication (VLC, LiFi)
- Channel measurements at 300 GHz

Research for the next generation wireless communication

„THz and VLC are potential technologies of B5G and 6G"

Ultra high-speed channel coding

New waveforms, multiple access

Ultra-massive MIMO

Full-duplex communication

Cell-free massive MIMO

THz sensing & communication

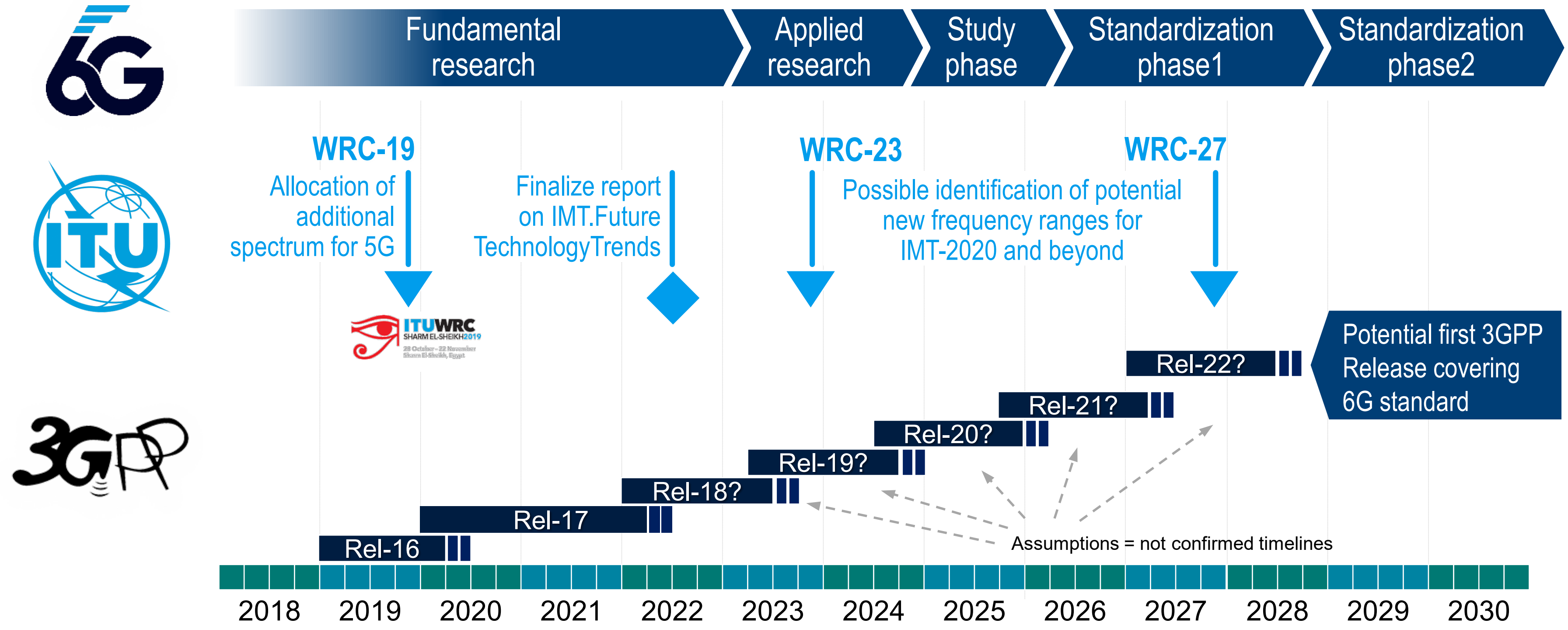
Visible light communication

Intelligent reflecting surfaces

Distributed processing

AI and Machine Learning

Future standardization and regulatory roadmap



*) *IMT-2020 systems are usually called 5G. The ITU has already started a new report to prepare the work on IMT-2020 and beyond that is likely to become 6G*

From 5G applications to a 6G vision

Meters (Gas,..),
Home automation,
Wearables

Gaming,
Car2Car Communication,
Factory automation

Possible 6G applications

360° HD AR/XR

Autonomous driving

Industrial networks

Digital twins

Urban Air Mobility

Sensing / holograms

Remote health care

BMBF “6G Hubs”

250 MEUR (4 hubs for 4 years) for by the Federal Ministry of Education and Research (BMBF)

6G-life

- https://6g-life.de/
- TU Munich, TU Dresden
- research for 6G communication networks with a focus on human-machine collaboration
- new approaches for sustainability, security, resilience and latency
- sustainably strengthen the economy and thus digital souvereignty in Germany

6G Research and Innovation Cluster (6G-RIC)

- Fraunhofer Heinrich-Hertz-Institute, TU Berlin, Fraunhofer IAF, IHP etc.
- open interfaces beyond technology boundaries, ORAN
- AI and security by design
- Joint Communication and Sensing
- sub-THz communication, 6G radio and propagation, semiconductor heterointegration

Open6GHub

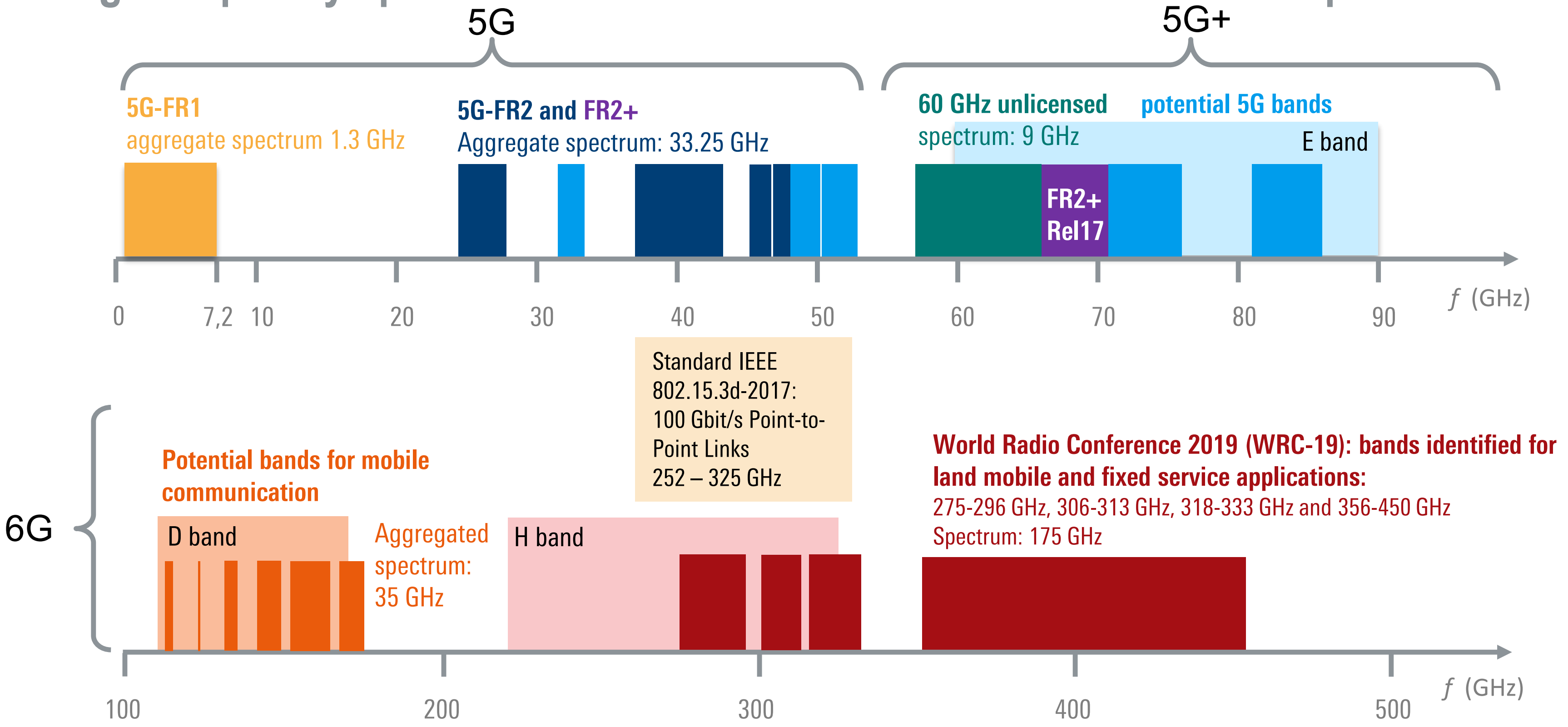
- https://www.dfki.de/web/news/detail/News/open6ghub-foerderung-bmbf/
- German Center for Artificial Intelligence (DFKI), TU Kaiserslautern
- Joint Communication and Sensing
- Intelligent Networks

6GEM: Research hub for open, efficient and secure mobile systems

- http://www.6gem.de
- RWTH Aachen, University Duisburg-Essen, RUB, TU Dortmund
- Test beds: autonomous driving, logistics & robotics, smart hospital

New spectrum for 5G and beyond: bandwith is the key

A huge frequency spectrum will be available at mm-wave and THz frequencies



Applications of THz waves

A phletora of applications yet to be explored.

Communication & Sensing

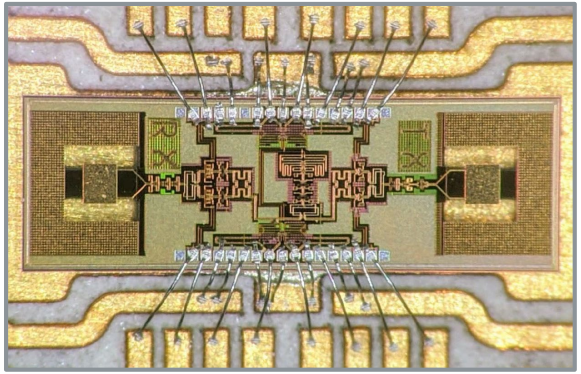
- Ultra-high speed communication
- Fusion of communication and sensing (radar) capabilities

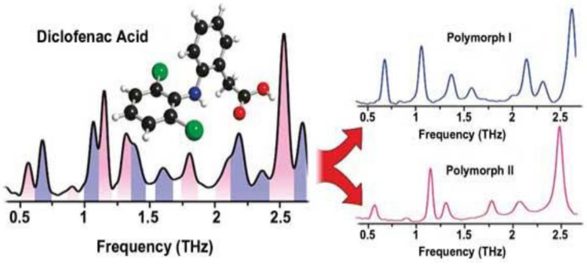
Spectroscopy

- material analysis
- example: analysis of the terahertz spectra from diclofenac acid (Voltaren) can distinguish between the two chief forms of the drug.

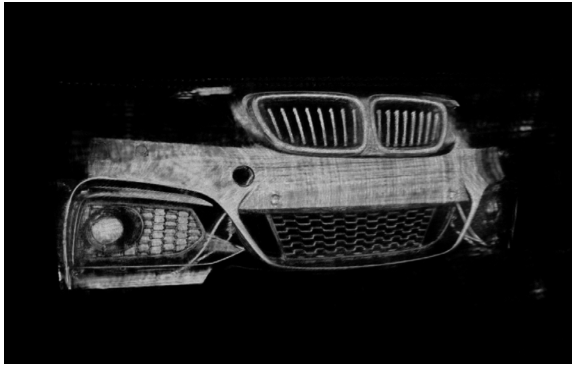
Imaging

- non-destructive imaging (security scanner with R&S QPS100)
- production line (check of configuration)





Courtesy of Analytical Chemistry



THz waves for communications: use cases

Can it work ? Use absorption windows, power and antenna arrays for directivity.

Backhaul / fronthaul links

- Ultra-high speed communication
- Front-/backhaul P2P connections
- infrastructure in remote locations

Kiosk & intra-device communication

- ultrafast download of pre-fixed content (UHD video, music, etc.) at specific locations (vending machines, train stations)
- chip-to-chip communication

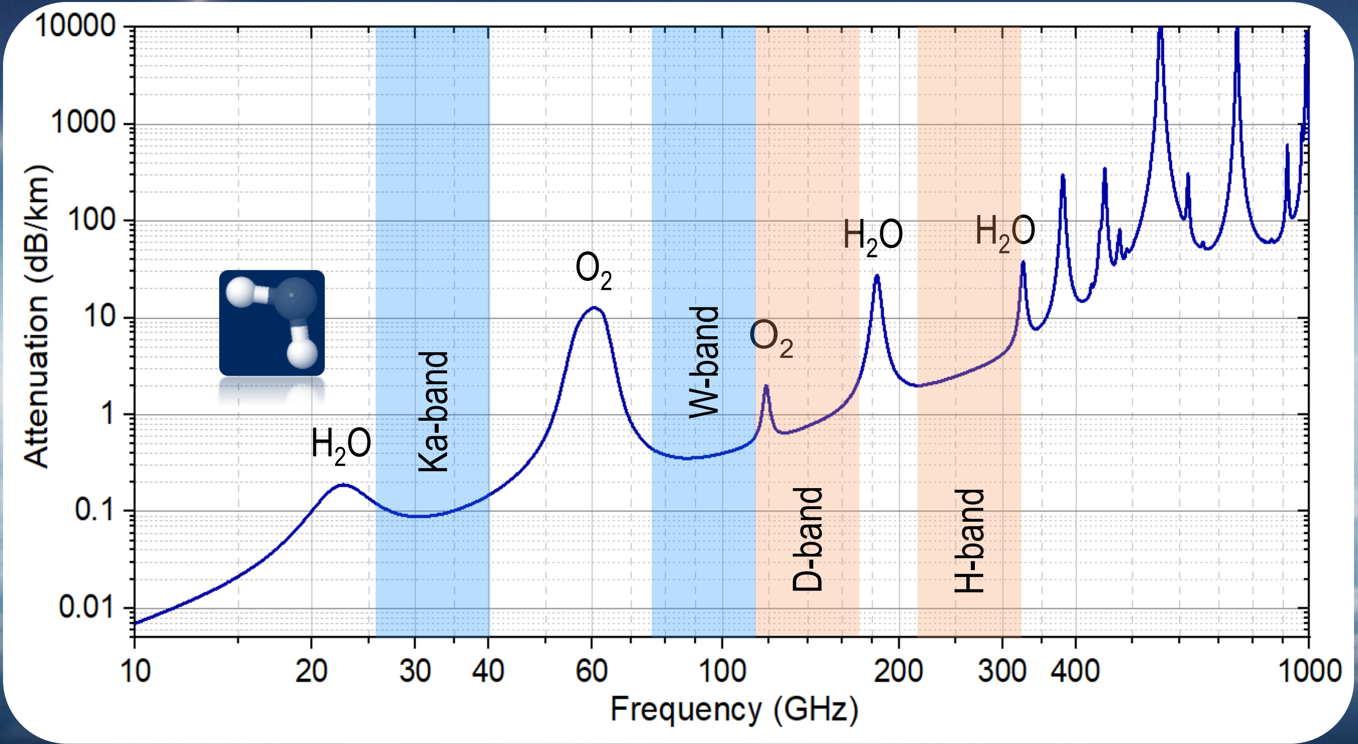
Wireless link in data centers

- communication inside data center: remote memory can increase design flexibility and reduce cost by extending CPU-memory distance.

Interaction of THz waves

How THz radiation interacts with matter defines how it can be applied

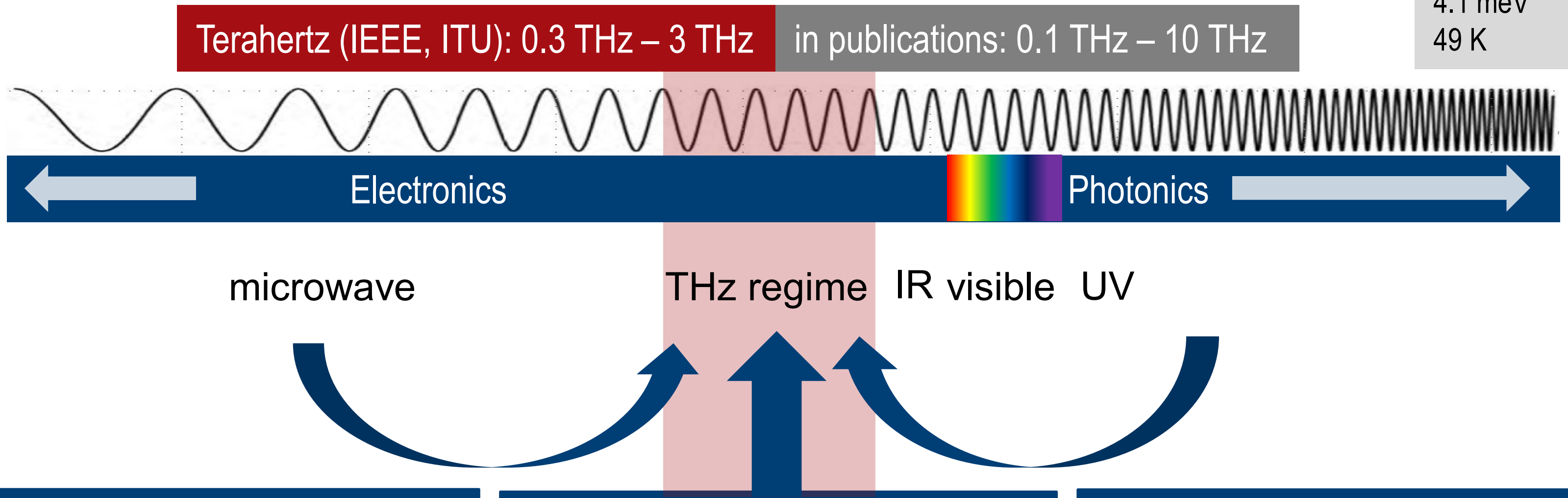
- **Energy / frequency region of molecular rotational transitions** of gas molecules and vibrational transitions of weak bonds.
- **low energy: does not initiate changes in chemical structure.**
- **Terahertz waves can penetrate** through materials opaque to other parts of the EM spectrum.



Ways to generate THz radiation

From Electronics to Optoelectronics

Energy equivalents:
1 THz
1 ps
300 µm
4.1 meV
49 K



Up-conversion: Electronic sources

- Multiplier chains, RTD, transistors, diodes
- compact, room temperature, but bandwidth limited, limited efficiency

Direct THz emission

- QCL (quantum cascade laser), non-linear optics, molecular lasers (power OK, limited efficiency, sometimes cryogenic)

Down-conversion: Opto-Electronics

- Photodiodes, photoconductors
- tunable, room temperature, but power limited, limited efficiency

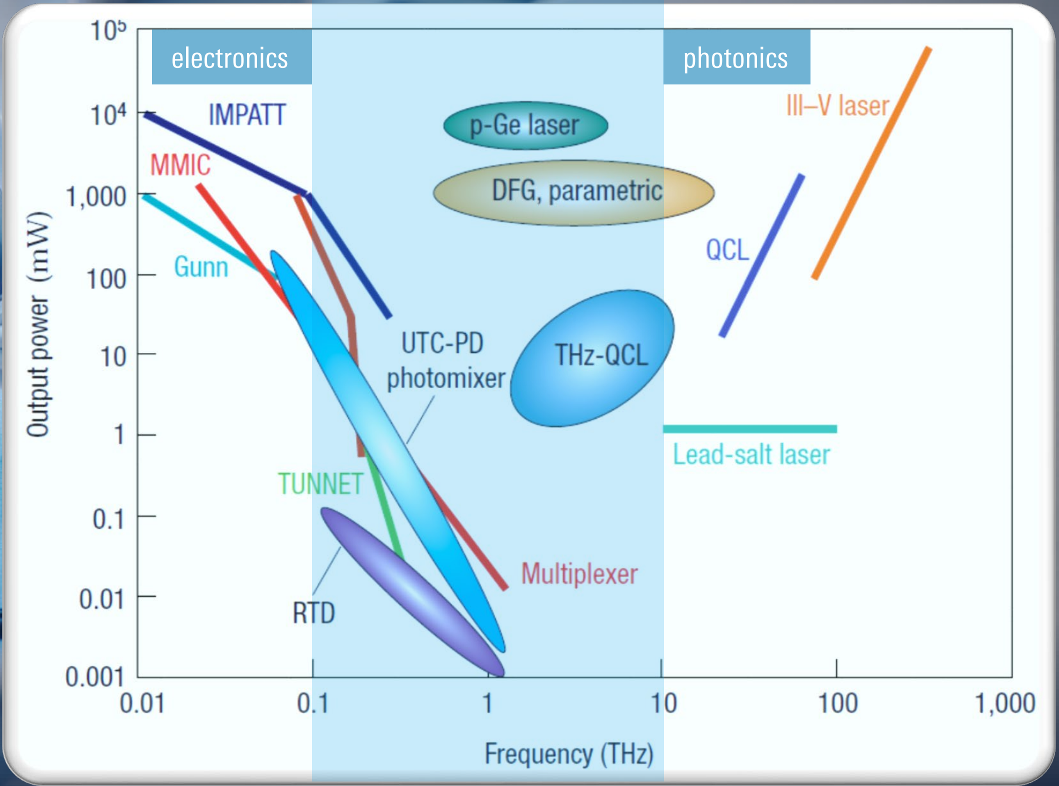
Up-conversion
R&S core technology

Designed for radiated spurious emission (RSE) measurements
- TC-MX140 supporting 90 GHz to 140 GHz
- TC-MX200 supporting 140 GHz to 200 GHz
- Extension for 200 GHz to 325 GHz in preparation

D-band (110 to 170 GHz) demonstrator setup

„The THz Gap“

Sources for THz radiation on the borderline between electronics and photonics



THz-QCL: quantum cascase laser

RTD: resonant tunneling diode

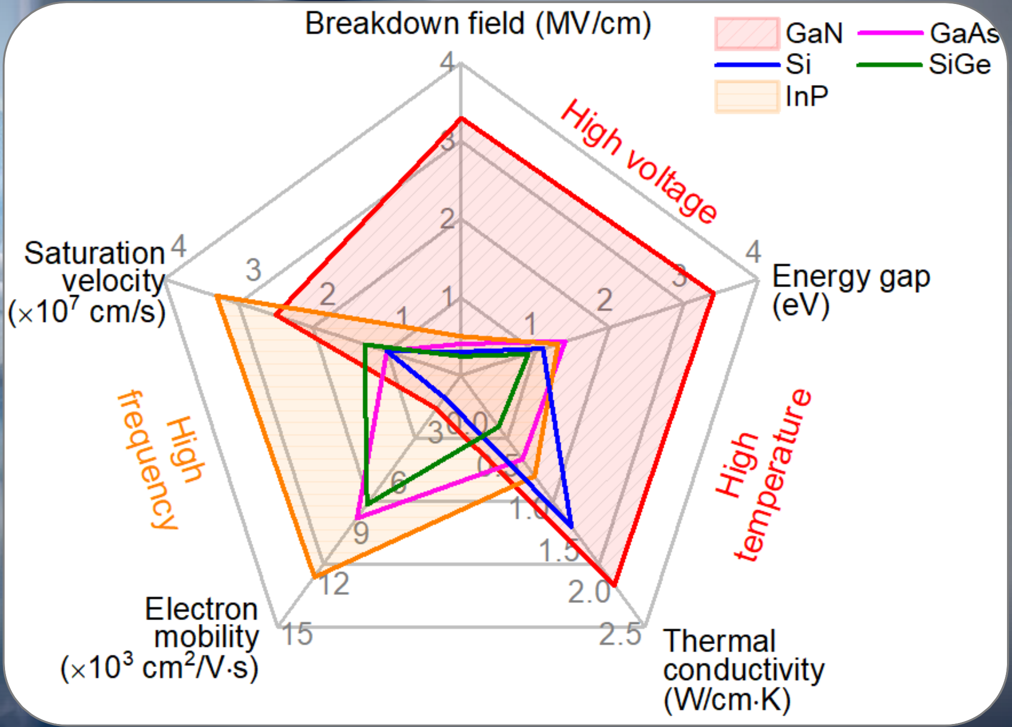
UTC-PD: uni-traveling carrier photo diode

Reference:
"Cutting-edge terahertz technology"
Masayoshi Tonouchi
Nature Photonics volume 1, pages 97–105

Material properties of semicondctors for high-frequency applications
High power at high frequencies: III-V semiconductors (GaN, InP) vs. Silicon

Different worlds:

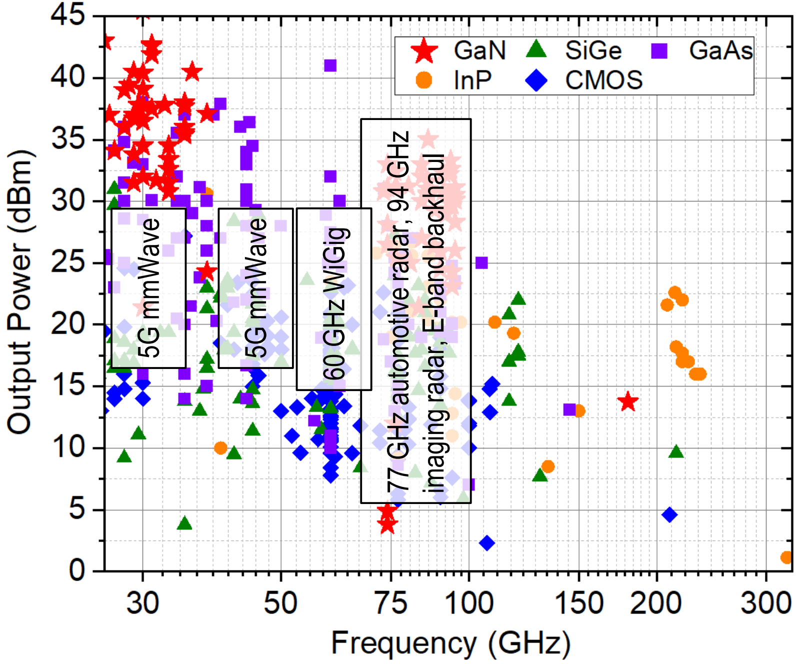
- **InP:** highest electron mobility and saturation velocity
- **GaN:** high electron mobility in combination with high breakdown voltage and thermal conductivity (power amplifier MMICs)
- **SiGe:** advantage with the perspective to combine with **CMOS** for lower-cost commercial applications



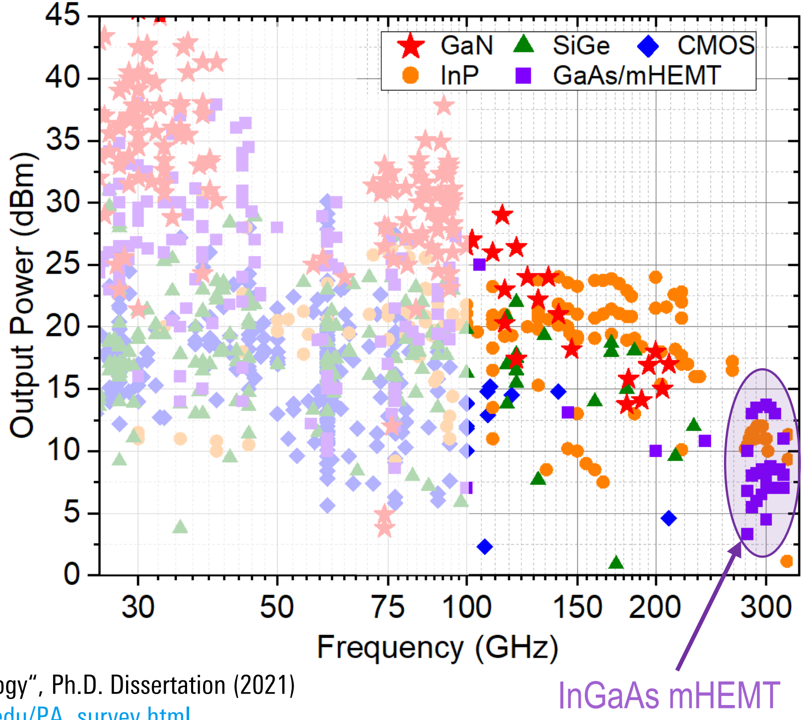
Overview of state-of-the-art mm-wave power amplifiers

B5G and 6G are pushing the frequency boundaries, data is bunched around the driving applications.

2000 - 2016



2000 - Oct 2020



References: M. Cwiklinski, „Design of Millimeter-Wave Power Amplifiers in GaN HEMT Technology“, Ph.D. Dissertation (2021)
H. Wang et al., "Power Amplifiers Performance Survey 2000-Present“, https://gems.ece.gatech.edu/PA_survey.html

6G – D-band over-the-air measurements for sub-THz research

Extending OTA antenna measurements into the D-band for exploring sub-THz communication

sub-THz frequencies for data rates towards Tbps

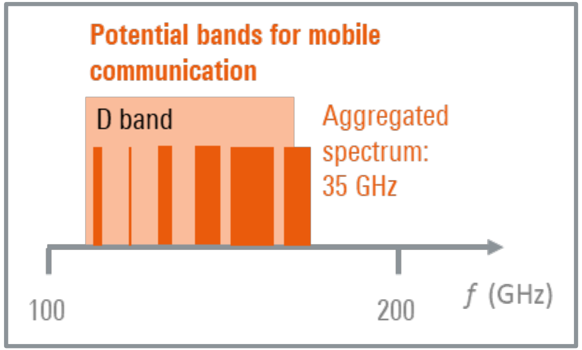
- New spectrum with large available bandwiths is the key for highest data rates:
  - **5G mmWave** 28 GHz and 39 GHz
  - **future frequencies for 6G** > 100 GHz in the D-band (110-170 GHz) and beyond

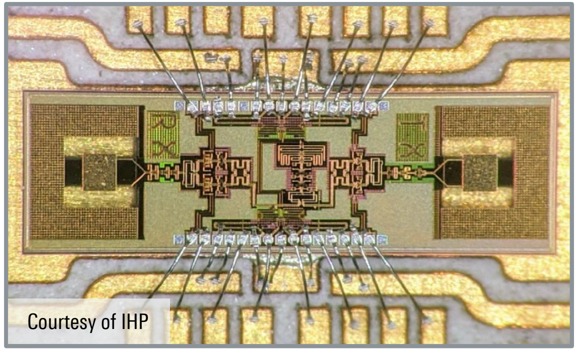
Communication and Sensing

- Future 6G devices might reach into the sub-Terahertz spectrum for ultra-high speed communication & sensing
- Devices will incorporate **highly integrated active antenna systems** for massive MIMO and sensing applications.

Over-the-air testing (OTA) with the ATS1000

- The ATS1000 simplifies the testing needs because no mechanical modification and no additional RF cabling is required to measure the amplitude and phase coherent response of a DUT in the frequency range from 110 GHz to 170 GHz**.**

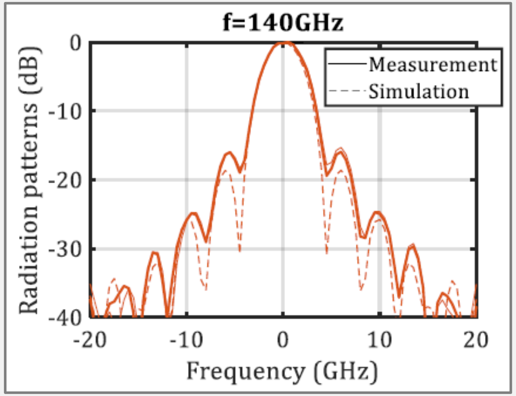




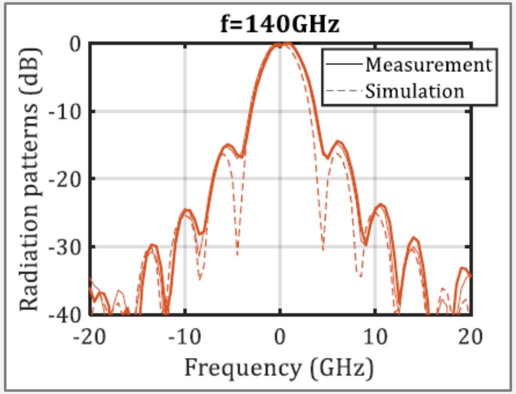
EXEMPLARY MEASUREMENT RESULTS

► Simulation and measurement results show excellent agreement

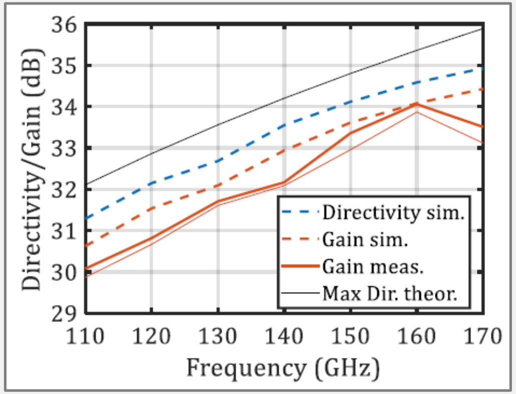
Broadside Φ=0° (E-plane)



Broadside Φ=90° (H-plane)

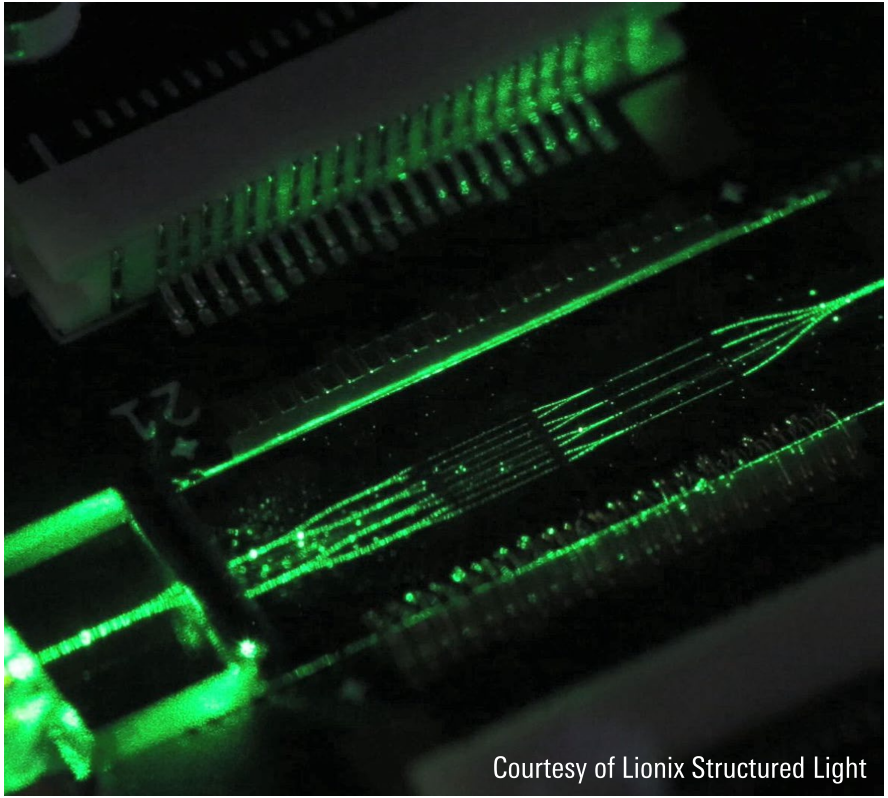


Broadside Gain over Frequency



Photonics for wireless communication

Why optical technologies now ?



Courtesy of Lionix Structured Light

Why optical now ?

- Photonics is set to represent to the 21st century, what electronics has meant for the 20th century.
- Recent feedback from key customers has sparked new interest in applying optical technolgies for wireless communication (timing even before „6G“ 2030) but also for sensing and other applications.
- core network infrastructure, optical interfaces for high throughput (also at chip-level)

Visible light communication (VLC)

- VLC a.k.a. optical wireless communiation, LiFi (Fraunhofer HHI, CMRI)
- modulation of commercial LEDs (cost-efficient with easy integration into existing infrastructure)
- in the future use of VCSEL (vertical cavity surface emitting laser) arrays.

THz radiation via optoelectronics:

- Alternative method to generate THz radiation by optical mixing on a photodiode (IEMN Lille, Fraunhofer HHI, TOPTICA TeraScan). Currently still bulky setup, but integration and miniaturization is ongoing.

Optical Wireless Communication / VLC / LiFi

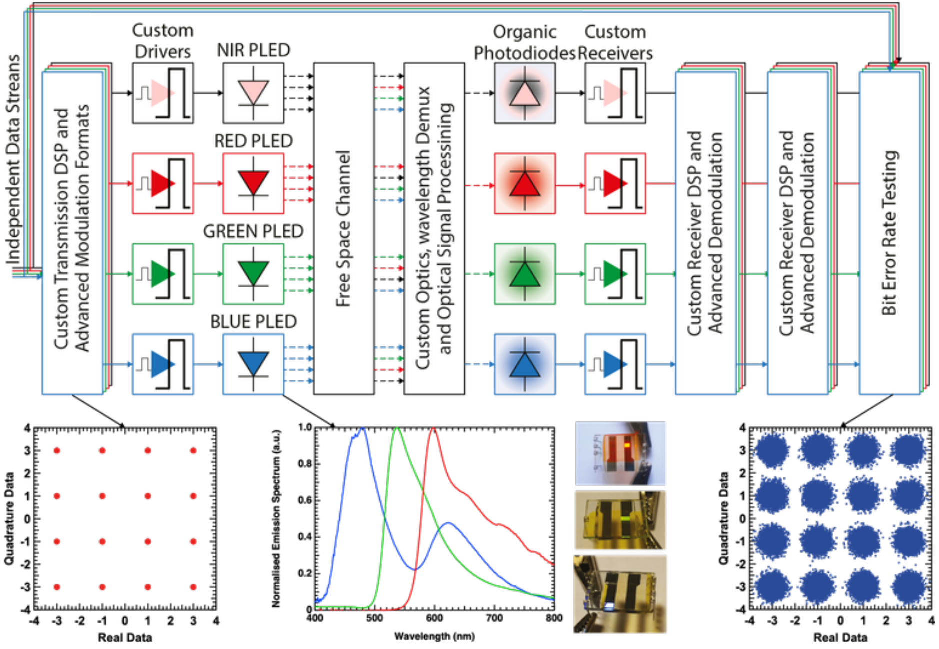
Cost-effective alternative to THz ?

VLC higher layers:

- activities to use existing communication standards (such as WiFi) because of the cost factor for chipset vendors to address a mass market (factor 10x higher than previously used power line communication PLC standard).
- PHY is ITU-T G.9991 G.vlc and IEEE 802.15.13.

VLC testbed HHI:

- LED-based frontends, driver core know-how (200 MHz), MATLAB-based software toolkit to generate waveforms



Courtesy of UCL: VCL with organic semiconductors

Visible Light Communication (VLC)

Cost and energy-efficient alternative to THz for 6G ?

Energy efficiency / cost

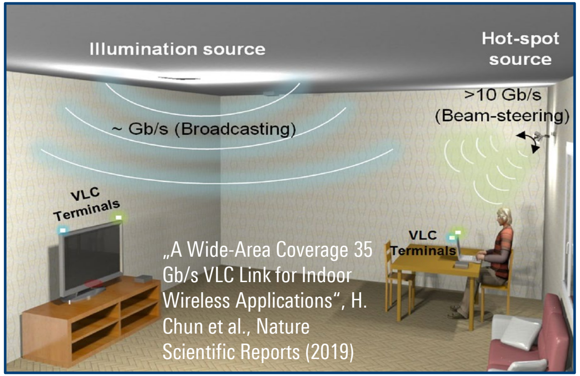
- intensity modulation of existing solid-state lighting infrastructure often provided by light-emitting diodes (LEDs)
- cost and energy-efficient mature technology alternative to THz communication ?
- dedicated LEDs with higher bandwidth

Spectrum

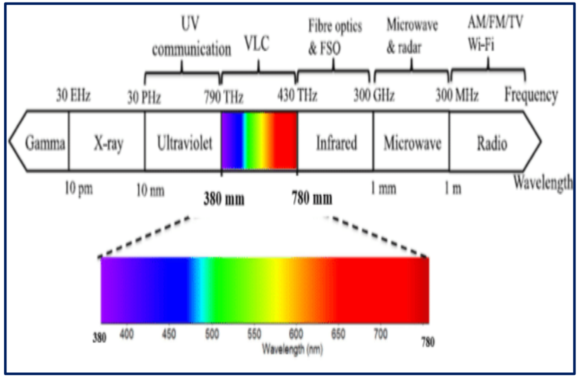
- VLC offers key advantages over traditional radio-frequency based access networks including approximately 300 THz of license free bandwidth carried on visible and IR wavelengths

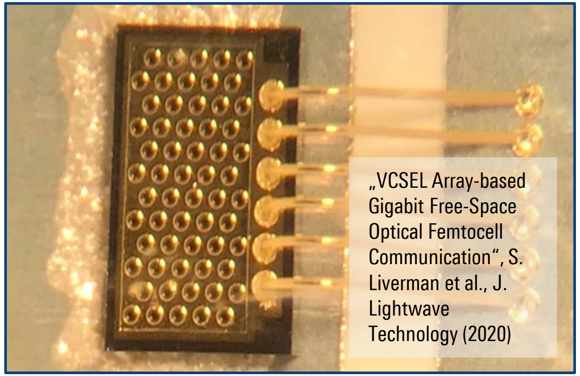
VCSEL for higher bandwidth

- use VCSEL (arrays) instead of LEDs
- higher modulation bandwidths up to several GHz possible with high currents
- already used large-scale for face scanning in smartphones
- *below picture*: 850 nm VCSEL 60-element array light source



„A Wide-Area Coverage 35 Gb/s VLC Link for Indoor Wireless Applications“, H. Chun et al., Nature Scientific Reports (2019)





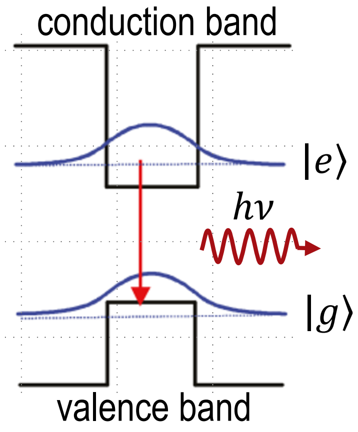
„VCSEL Array-based Gigabit Free-Space Optical Femtocell Communication“, S. Liverman et al., J. Lightwave Technology (2020)

Direct THz Generation: Quantum cascade laser (QCL)

THz vs. optical frequencies (Interband vs. intraband transition)

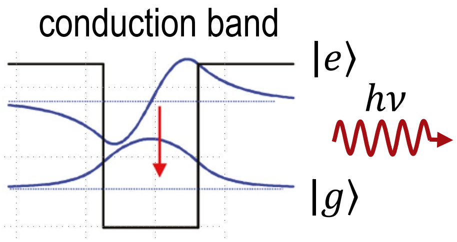
Interband diode laser

- Interband diode lasers cheap efficient for visible and IR frequency region
- THz photon energies are 100-1000x smaller than visible photons !
- No materials with such small bandgap and population inversion.
- GaAs / GaN are the standard semiconductor materials (III-V direct bandgap)



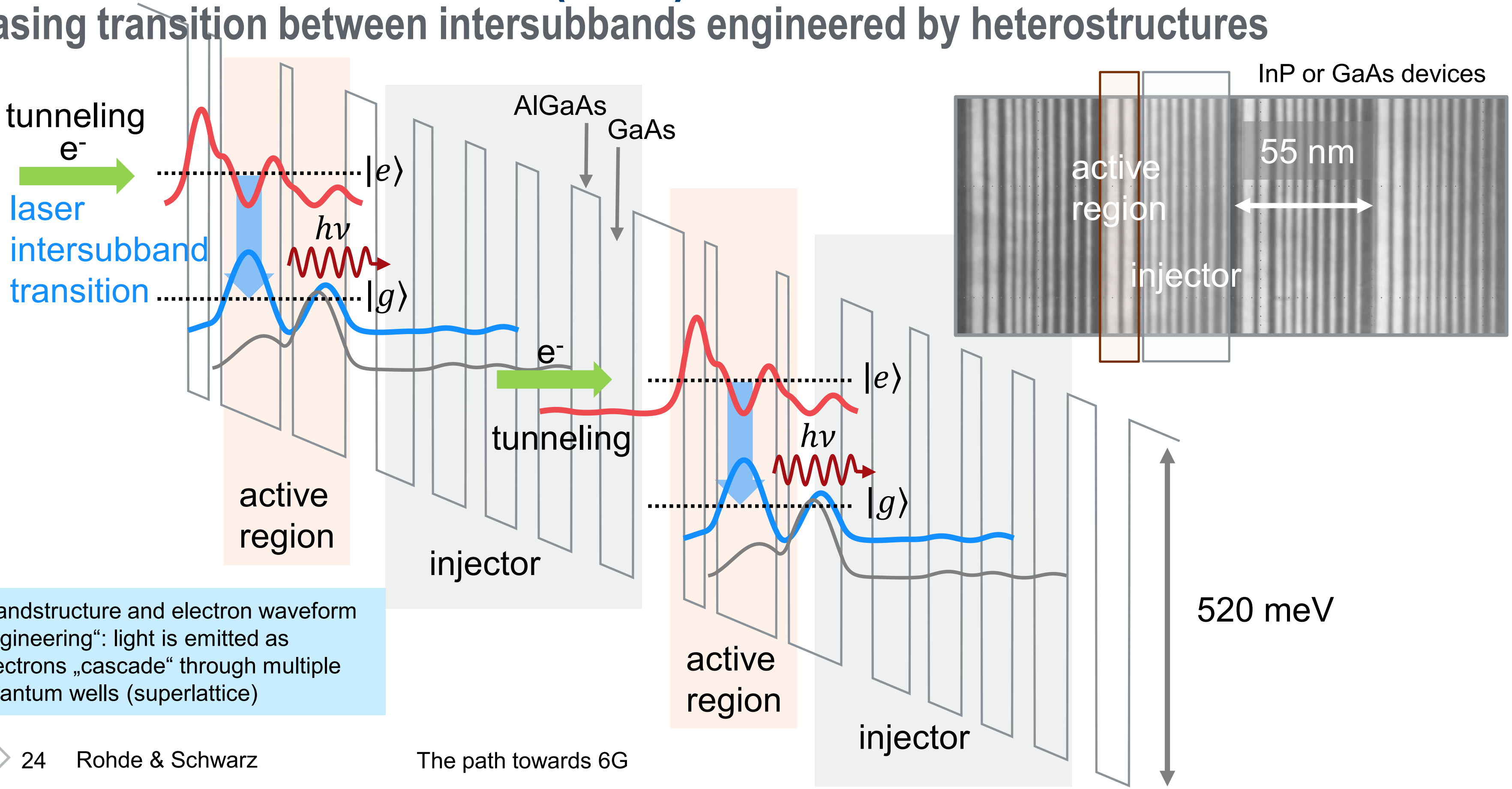
QCL

- Operating principle: Photons are emitted via intersubband transitions of electrons. Electrons tunnel resonantly into the quantum well of the next active region (cascading) and emits again.
- Electron wavefunctions: Each semiconductor layer is only a few atomic layers thin. The laser wavelength is designed by "Wavefunction engineering".



Quantum cascade laser (QCL)

Lasing transition between intersubbands engineered by heterostructures

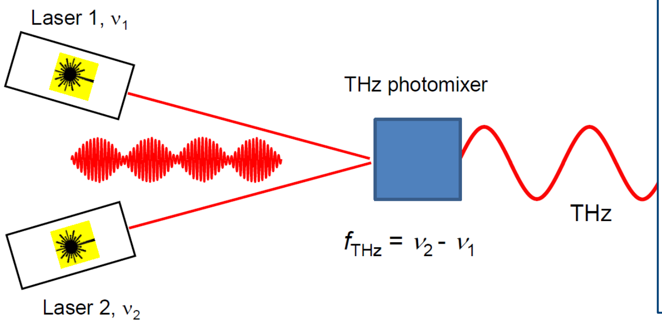


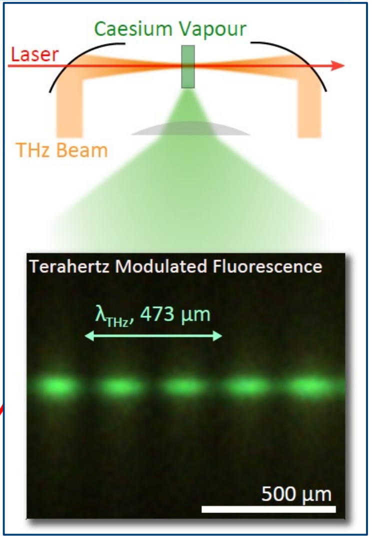
„bandstructure and electron waveform engineering“: light is emitted as electrons „cascade“ through multiple quantum wells (superlattice)

Down-conversion: Optoelectronic THz Generation

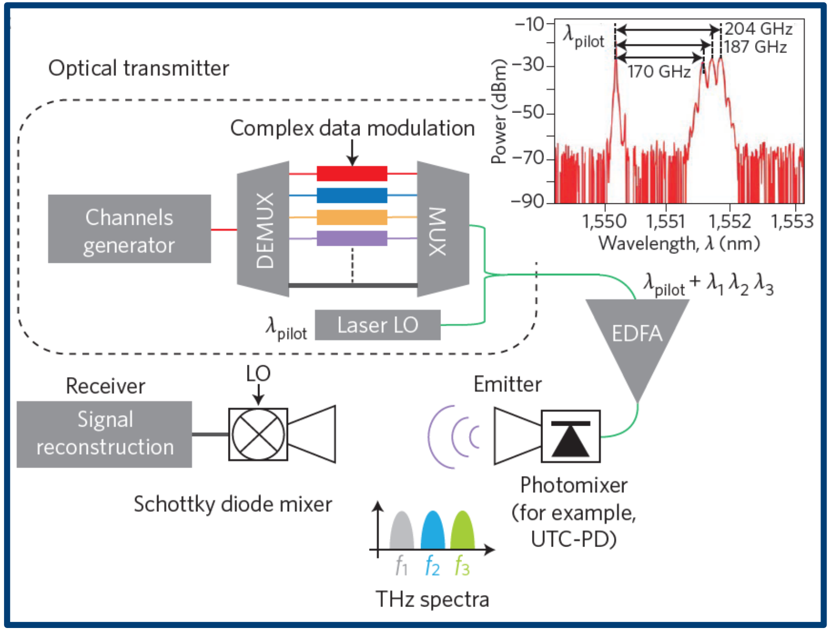
Photomixer: unitraveling carrier photodiode (UTC-PD)

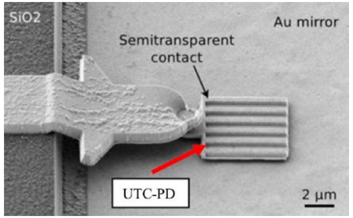
- The photomixer: a quadratic converter
- THz photomixer = (Photoconductor Photodiode) + Antenna
- Photonics: advantage is wide tunability with suitable antenna





Reference: „Real-time near-field terahertz imaging with atomic optical fluorescence ", C.G.Wade et al., Nature Photonics 11, pages 40–43 (2017)

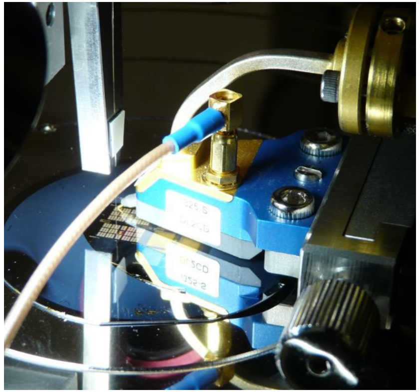




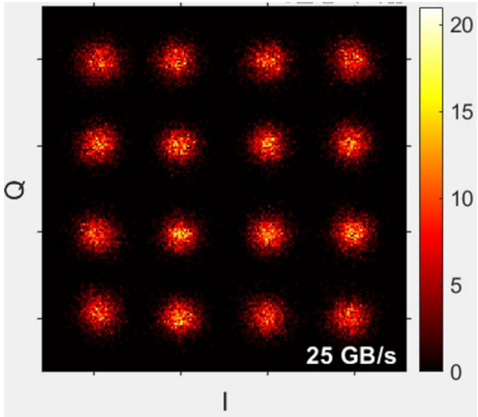
Reference: „Advances in terahertz communications accelerated by photonics", T. Nagatsuma, G. Ducournau & C. Renaud Nature Photonics volume 10, pages 371–379 (2016)

THz waves for communications

It can work !

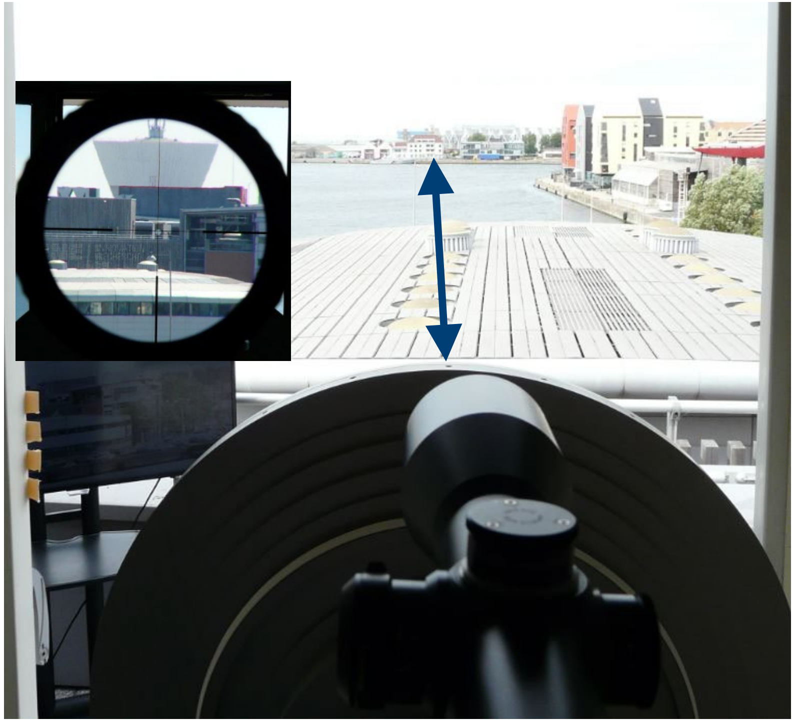


THz UTC-PD tested in lab
for 100 Gbit/s - 300 GHz



320 GHz carrier frequency –
100 Gbit/s

300 GHz live link, June 2017
850 m



https://youtu.be/laE-K6Pj_Rk

Université de Lille cnrs PhLAM iemn

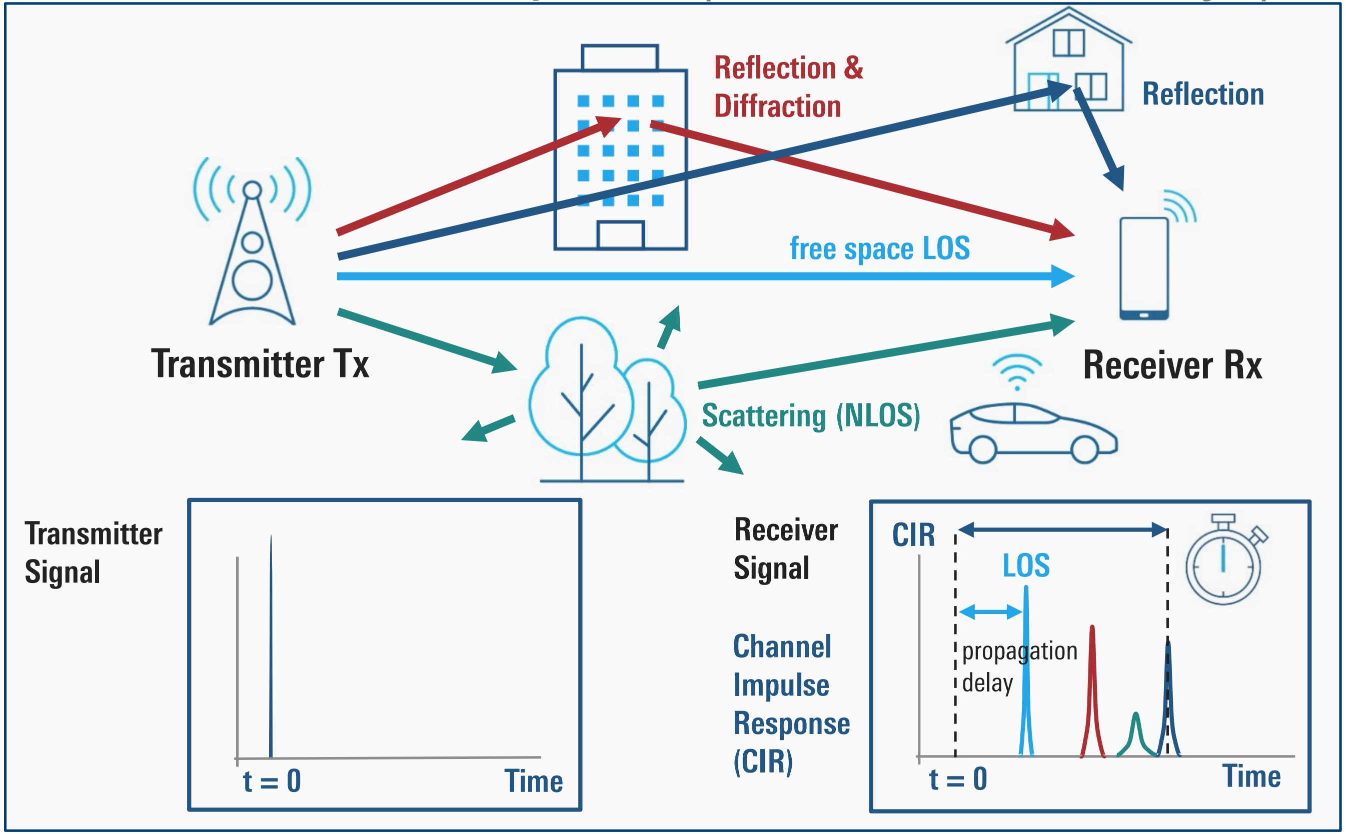
Courtesy of:
Prof. G. Ducournau, IEMN, CNRS-Université de Lille
PhLAM, CPER Photonics, Hauts de France Region, FRANCE

From channel sounding to channel models for Beyond 5G

Propagation characteristics at mmWave and THz frequencies (foundation for new PHY layer)

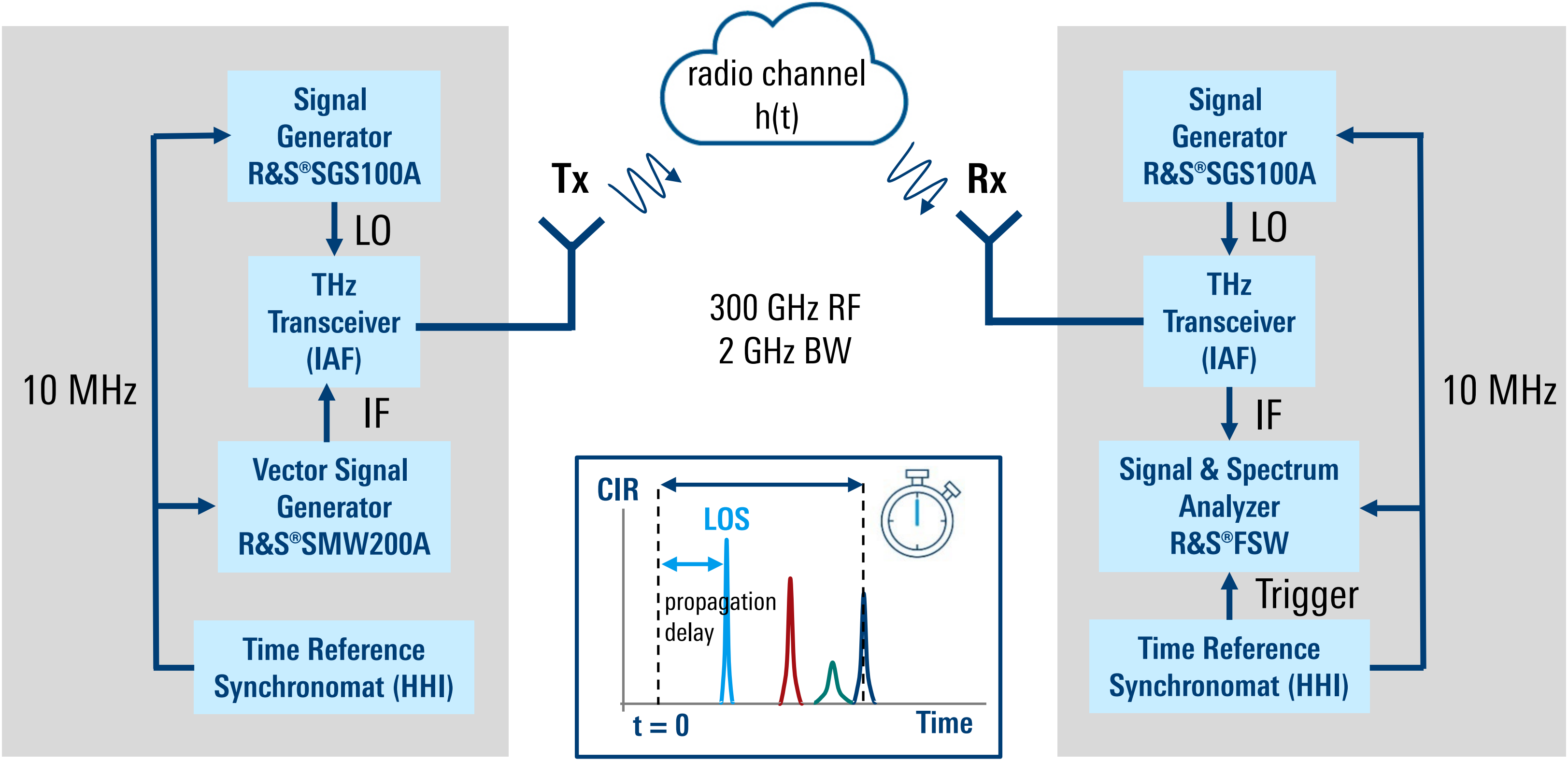
Key concepts:

- Channel models are needed for system performance evaluation
- Link and system level simulations for new PHY layer: pilot distribution in time and frequency
- 3GPP Channel models are standardized for fair comparison of simulation results
- New challenges with 5G-mmWave and Beyond 5G
  - Extremely extended frequency range up to 100 GHz and beyond 100 GHz for 6G
  - Spatial information / 3D beamforming



Time domain channel sounding setup at 300 GHz

Propagation delay measurement between transmitter and receiver

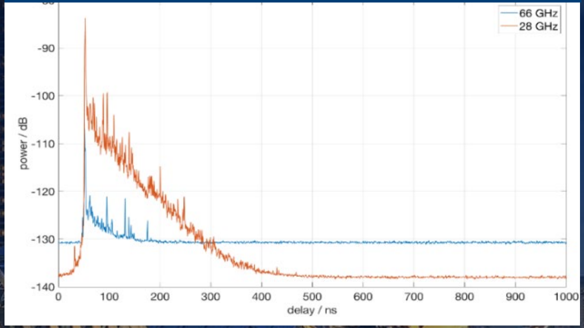


Collaborative Research with NTT DOCOMO and Fraunhofer HHI

5G channel models in industrial scenarios for 3GPP: production environment measurement campaigns in Memmingen and Teisnach plants

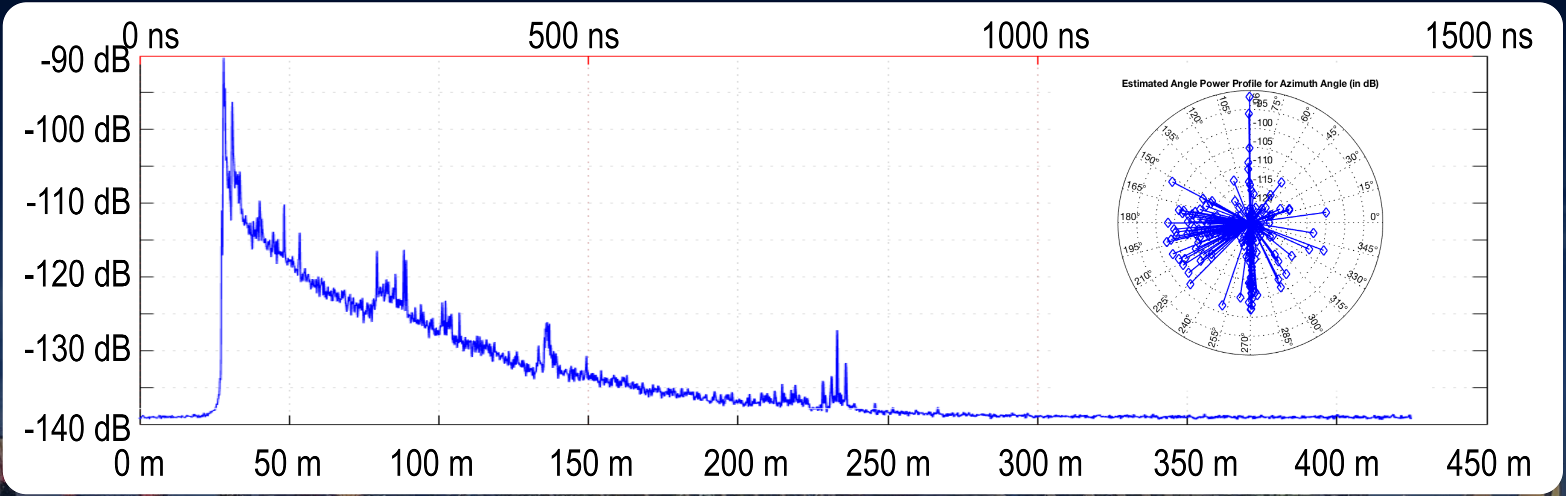
Measurement Campaign at 3.7 GHz, 28 GHz and 67 GHz

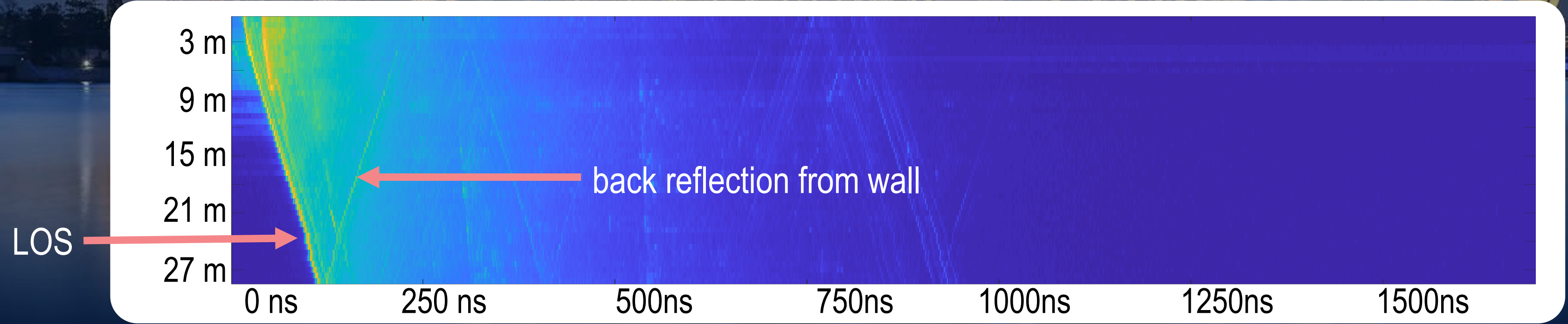
Power Delay Profile



„Measurement and Characterization of an Indoor Industrial Environment at 3.7 and 28 GHz" (EuCAP2020)
https://ieeexplore.ieee.org/document/9135943
„THz Channel Sounding: Design and Validation of a High Performance Channel Sounder at 300 GHz" (IEEE WCNC2020)
https://ieeexplore.ieee.org/document/9124887

Averaged Power Delay Profile (28 GHz Line-of-Sight)

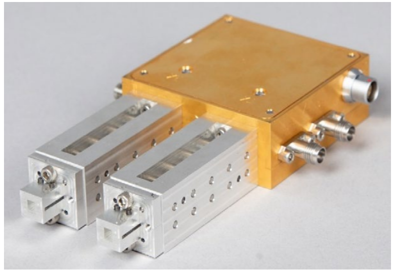




Research cooperation with Fraunhofer IAF and HHI at THz frequencies

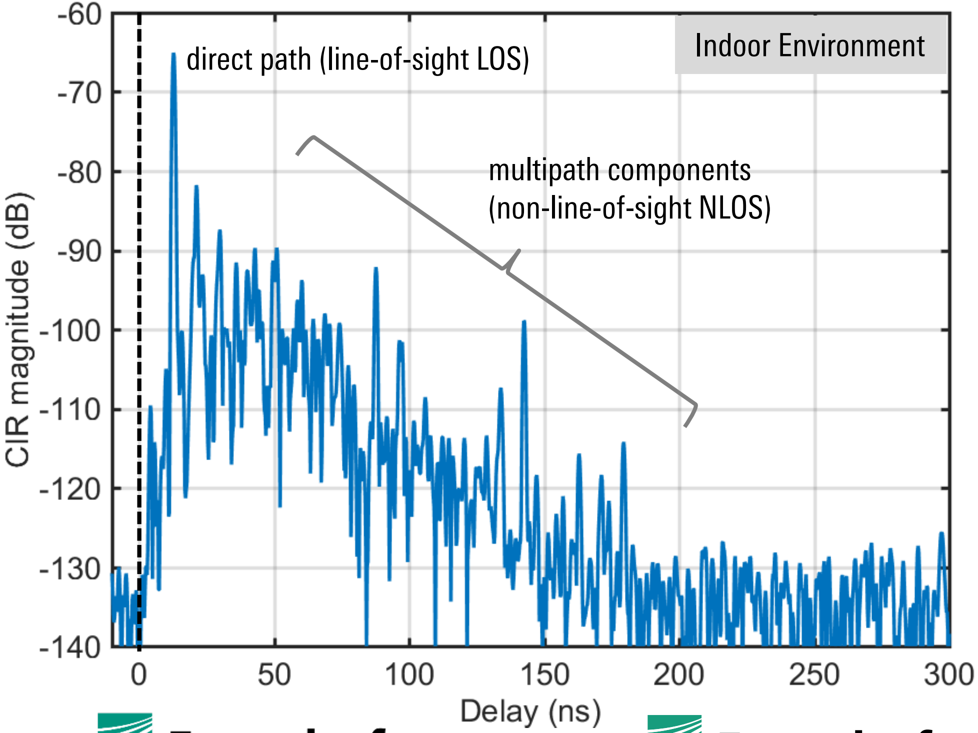
Channel impulse response CIR of indoor environment at 300 GHz

- Fraunhofer IAF InGaAs mHEMT technology: extremely low-noise and broadband applications at room temperature
- Signal generation Tx and analysis Rx at 275–325 GHz operating frequency
- Signals can be arbitrary modulated for transmission experiments with Beyond 5G candidate waveforms for THz communication or for channel propagation measurements.



„THz Channel Sounding: Design and Validation of a High Performance Channel Sounder at 300 GHz" (IEEE WCNC2020)
https://ieeexplore.ieee.org/document/9124887

An electromagnetic wave travels approx. 30 cm in 1ns !

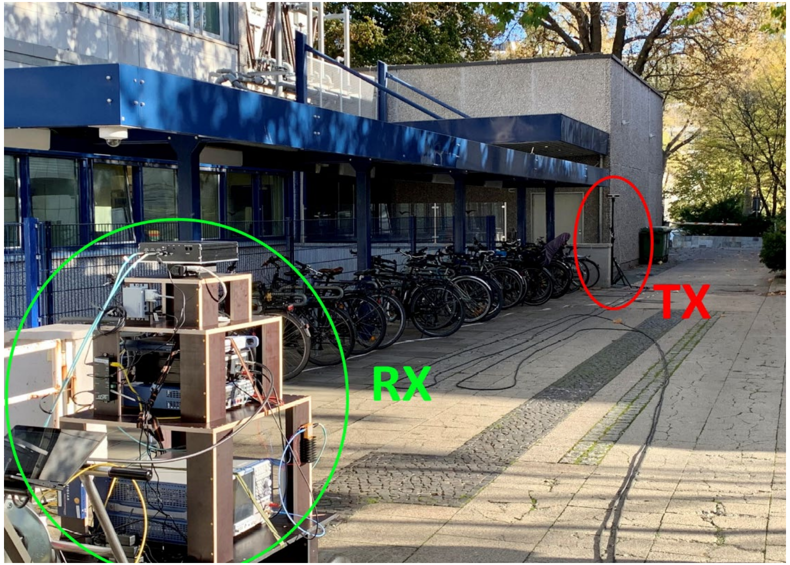


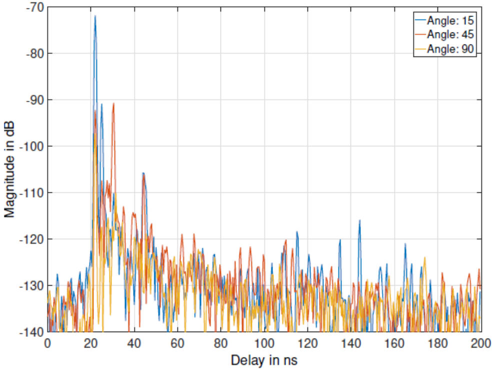
Fraunhofer IAF

Fraunhofer HHI

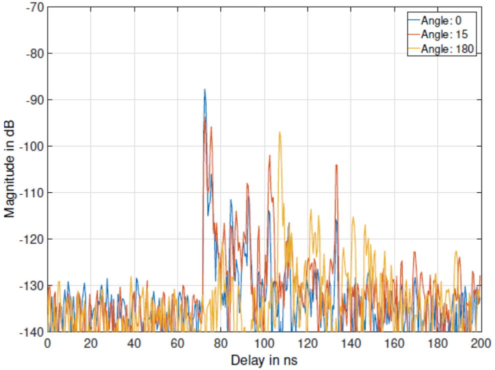
Research cooperation with Fraunhofer IAF and HHI at THz frequencies

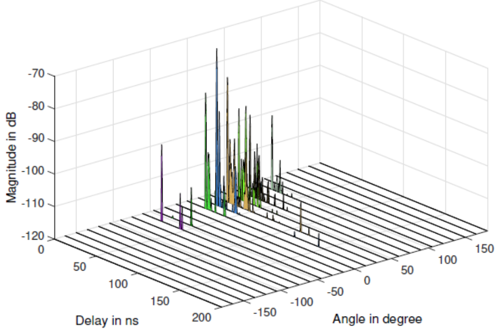
Channel impulse response CIR of outdoor environment at 300 GHz



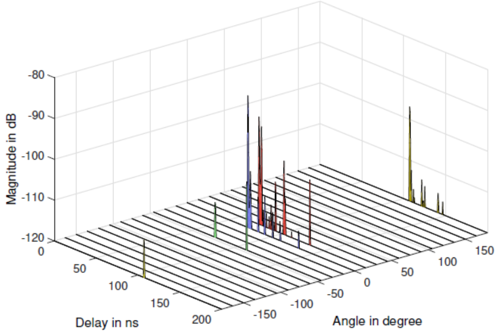


(a) Measurement Position 1





(a) Measurement position 1



(b) Measurement position 2

Fig. 5

„Angle-Resolved THz Channel Measurements at 300 GHz in an Outdoor Environment" in 2021 IEEE International Conference on Communications Workshops (ICC Workshops) https://ieeexplore.ieee.org/document/9473891

The future of mobile – 6G

- The European Vision*: “6G will bring a new era in which billions of things, humans, and connected vehicles, robots and drones will generate Zettabytes of digital information”
- 6G is targeting not only on pioneering integration of sensing and communication, but also the reduction of energy footprint, providing trustworthy network infrastructure, scalability, and affordability.

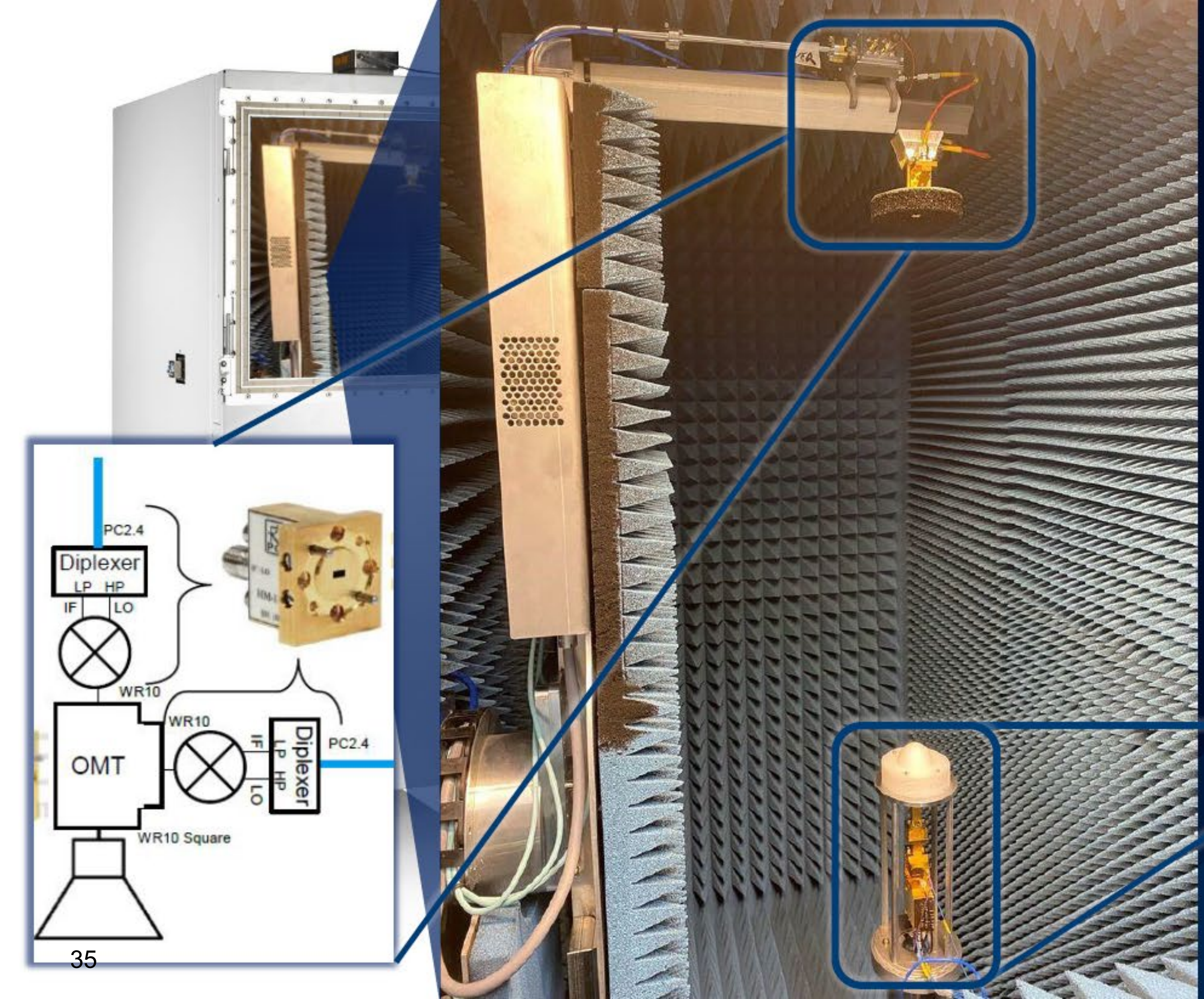
Source: 5GIA “European Vision for the 6G Network Ecosystem June 2021

We are already in the full swing with our cooperation partners to make the next mobile generation reality

Thank you !

ROHDE & SCHWARZ

Make ideas real



OVER-THE-AIR (OTA) TESTING

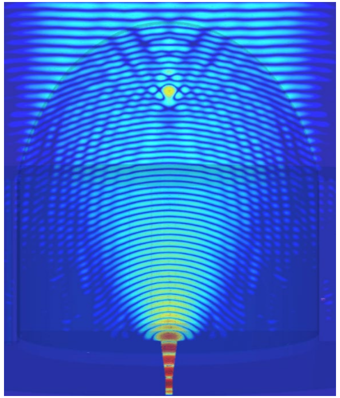
- Frequency extension of Antenna Test System 1000 (R&S®ATS1000) to support up to D-Band frequencies
- <u>Probe antenna</u> is a dual-polarized squared horn with an orthogonal mode transducer (OMT) to separate the two received polarizations (reciprocal)
- <u>DUT is lens antenna (110 to 170 GHz)</u>, measurement device R&S®ZNA43 vector network analyzer

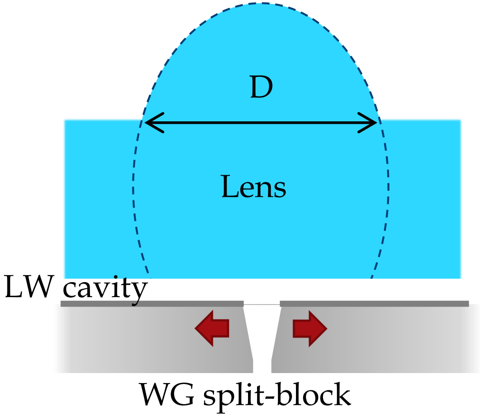
Device under test - IMST

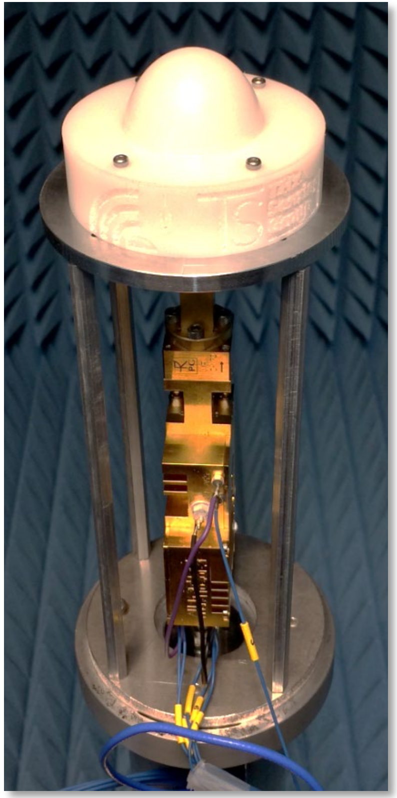
Highly directive lens antenna concept

- Elliptical lens made of low-cost, low-loss plastic with 35 mm diameter (20λ @170 GHz)
- Feed consists of λ/2 leaky-wave air cavity, excited by a WR6 WG
- Radiation pattern can be steered by displacing the feeder along the lens focal plane

Antenna Full-Wave Simulation



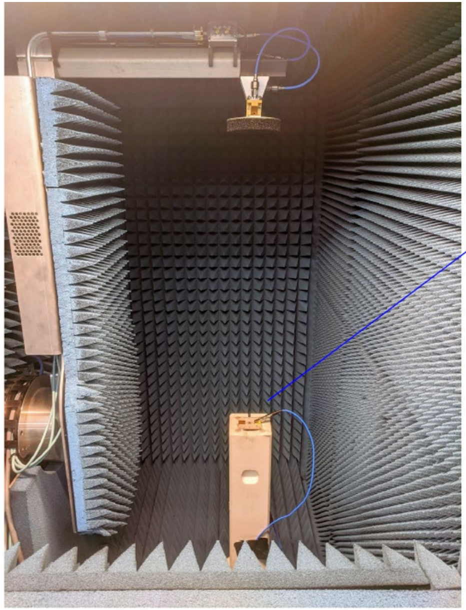


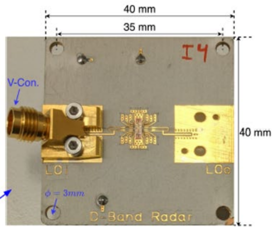


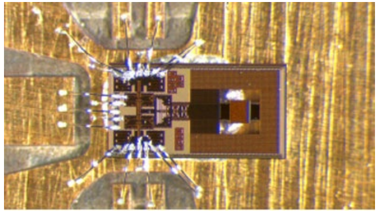
Design details and theory can be found in M. Arias Campo et al., "On the use of fly's eye lenses with leaky-wave feeds for wideband communications," IEEE Transactions on Antennas and Propagation, vol.68, no. 4, pp. 2480-2493, Apr. 2020.

Device under test - IHP PCB concept
Differential patch antenna for radar applications

- D-Band TX w/On-Chip Antenna in 130 nm SiGe BiCMOS
- 160 GHz single element transmitter with on chip antenna for various radar / gesture recognition applications.
- V-Connector for feeding a 40 GHz LO signal with different power levels
- On-board frequency-conversion up to 160 GHz
- Radiated EIRP can be controlled by SW







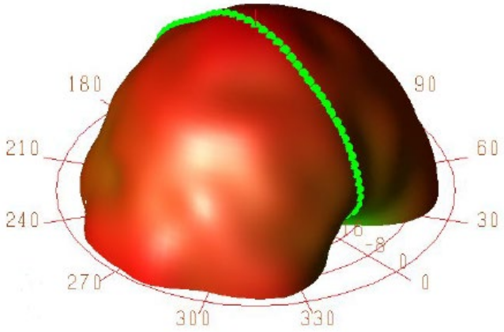
innovations for high performance microelectronics

"A Compact Efficient D-Band Micromachined On-Chip Differential Patch Antenna for Radar Applications*," 2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, Atlanta, GA, USA, 2019, pp. 2201-2202, doi: 10.1109/APUSNCURSINRSM.2019.8889358.

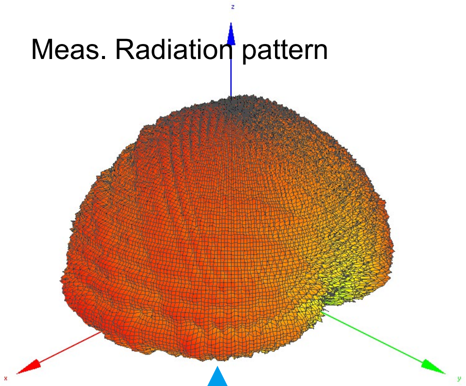
"Multimode W-Band and D-Band MIMO Scalable Radar Platform," in IEEE Transactions on Microwave Theory and Techniques, vol. 69, no. 1, pp. 1036-1047, Jan. 2021, doi: 10.1109/TMTT.2020.3038532.

2D cut:
Measurement results at 160 / 165 GHz

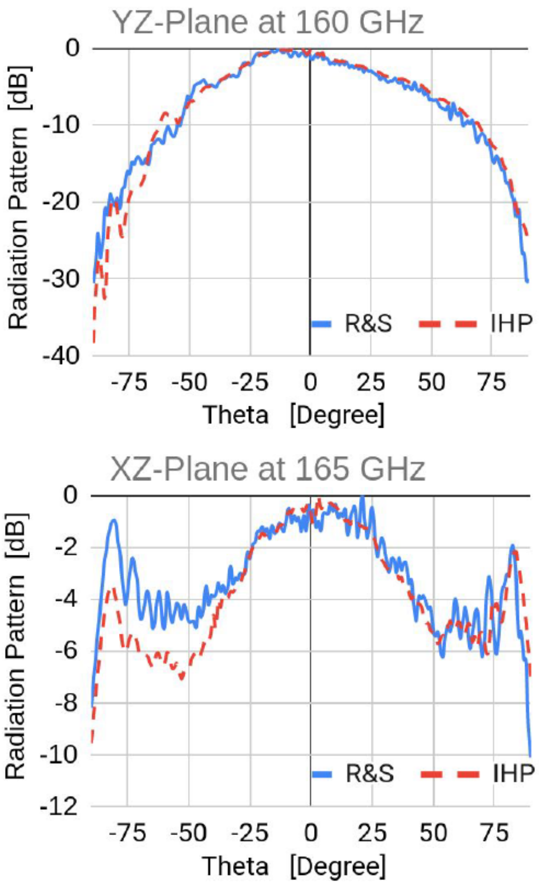
Simul. Radiation pattern



Meas. Radiation pattern



Pattern distortion and ripples
caused by a large PCB with V-conn.



- < 0.5 dB gain variation between meas. and simulation at boresight cuts at 0° and 90°