TOWARDS 6G: THE ROLE OF PHOTONICS IN THz COMMUNICATIONS

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ROHDE&SCHWARZ

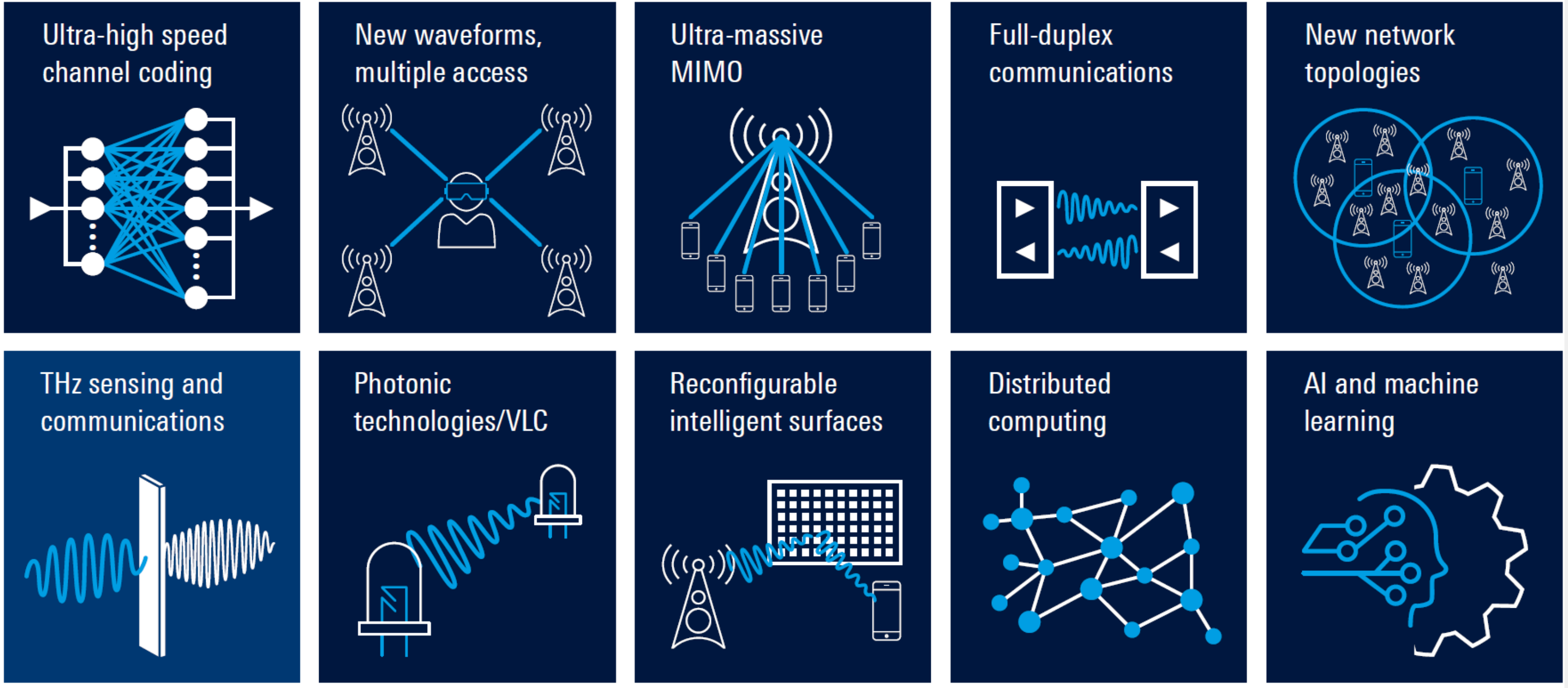
Make ideas real

Towards 6G: The role of photonics in THz communications

- THz potential use cases and spectrum landscape
- THz generation by electronic and photonic technologies
- 6G-ADLANTIK
- Phase noise measurements
- Optical frequency comb as microwave source
- OAM
- 6G sub-THz channel measurements in industrial environments
- Demo

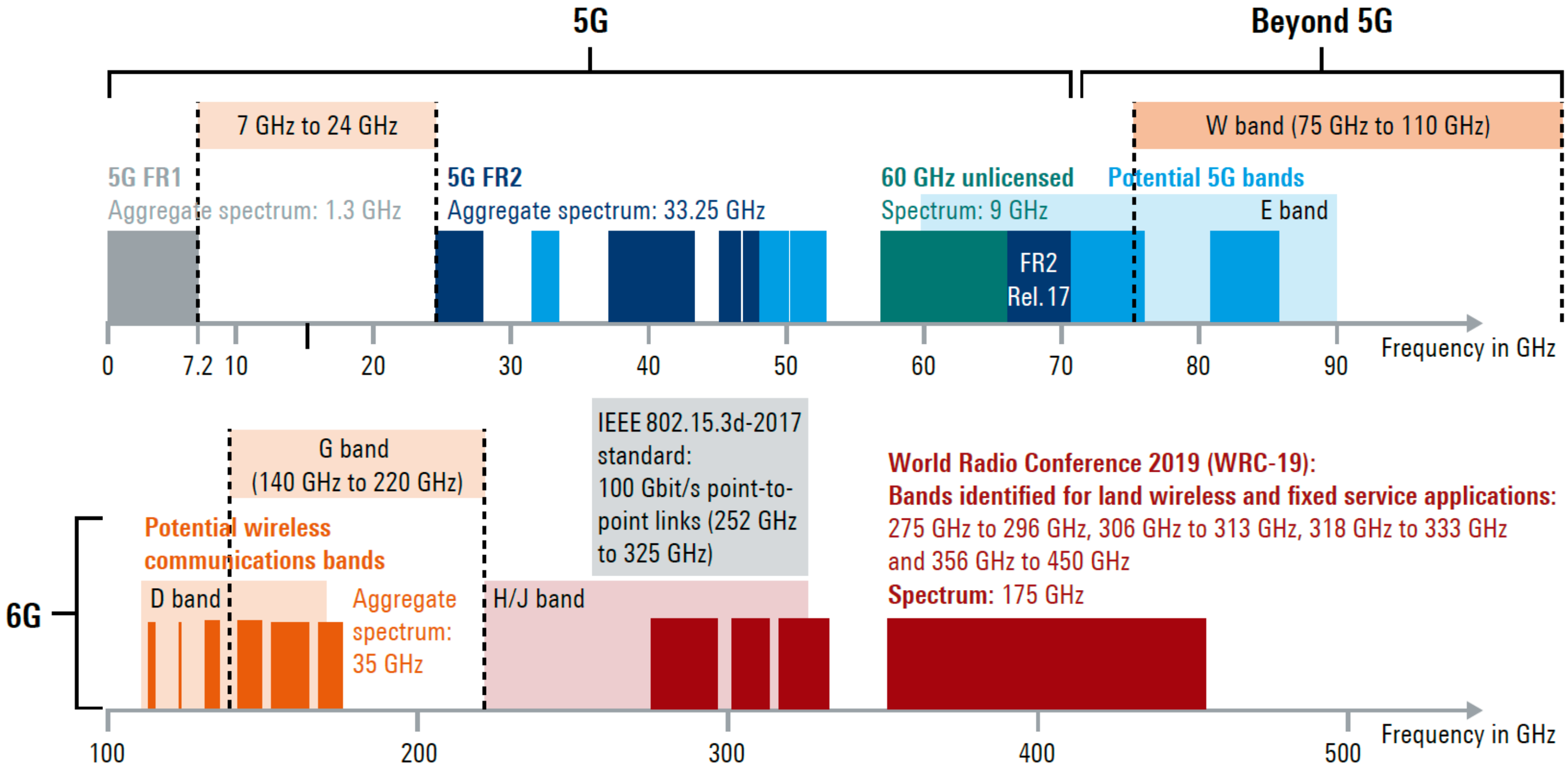
6G research areas - vision and key technologies

THz and photonics are potential technologies of 6G



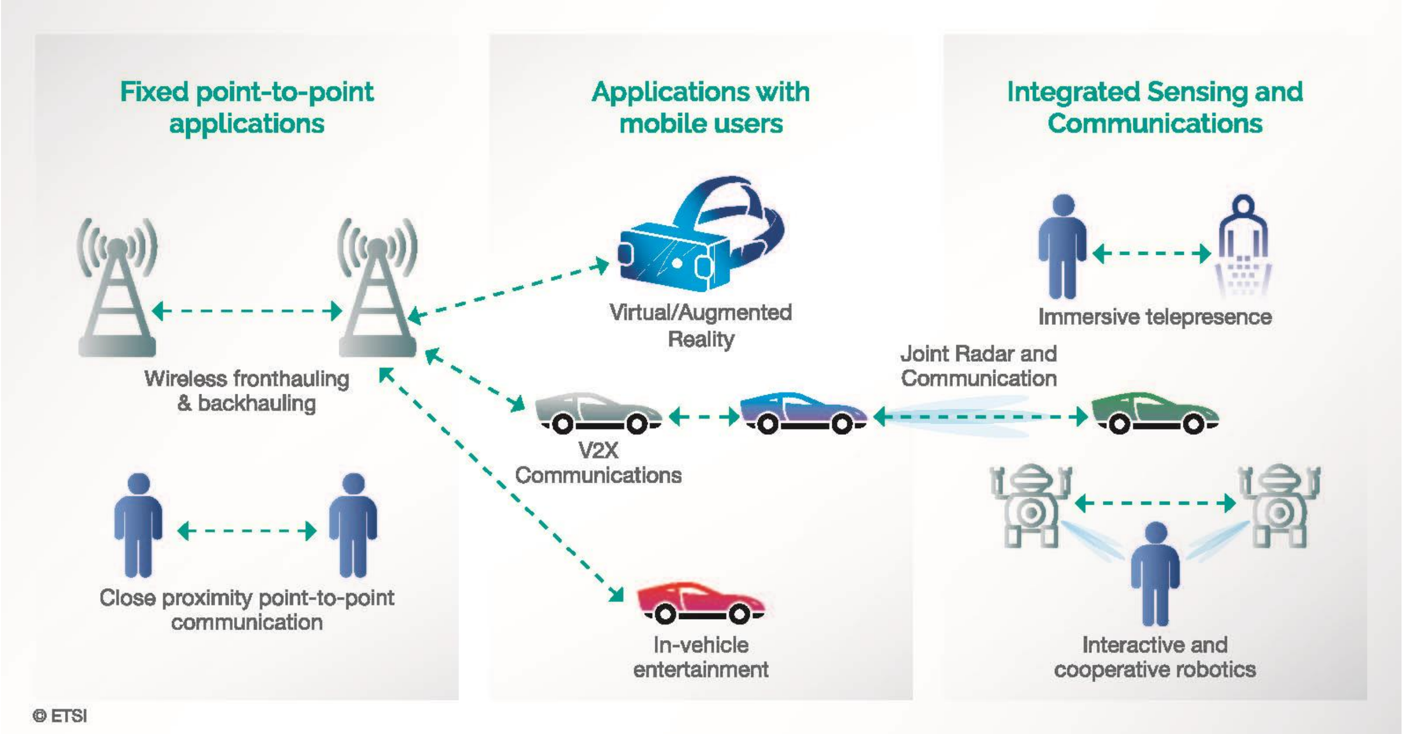
New spectrum for 5G and 6G: bandwidth is the key

Can sub-THz wireless networks score significant capacity gains in an energy efficient manner?



Estimated first use cases of THz Communication

What is expected to be realized first?



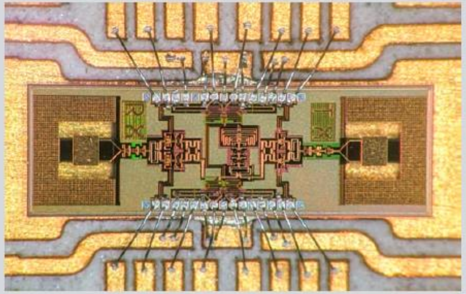
Source: T. Kürner, TeraHz – A candidate for 6G; Enjoy – The ETSI Magazine – January 2023, p. 14-15; [online] https://www.etsi.org/e-brochure/Magazine/January-2023/mobile/index.html#p=14

THz applications

A plethora of applications yet to be explored.

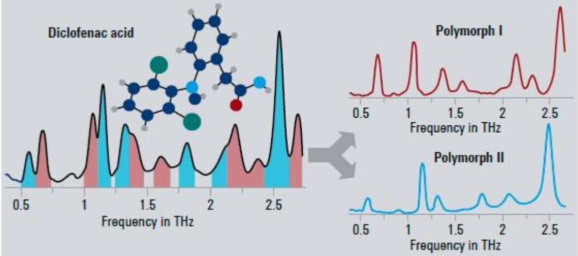
Communications and sensing

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



Spectroscopy

- Material analysis
- Analysis of the terahertz spectra from diclofenac acid can distinguish between the two chief forms of the drug



Imaging

- Nondestructive imaging (with R&S®QPS100 security scanner)
- Production line (final assembly test)

Estimated first use cases of THz Communication

What is expected to be realized first?

Backhaul/fronthaul links

- Ultra-high-speed communications
- Backhaul/fronthaul P2P connections
- Infrastructure in remote locations

Kiosk and intra-device communications

- Ultrafast download of prefixed content (e.g. UHD video, music) at specific locations (vending machines, train stations)
- Chip-to-chip communications

Wireless link in data centers

- Communications inside data centers: remote memory can increase design flexibility and reduce cost by extending CPU memory distance

absorption windows, power and antenna arrays for directivity

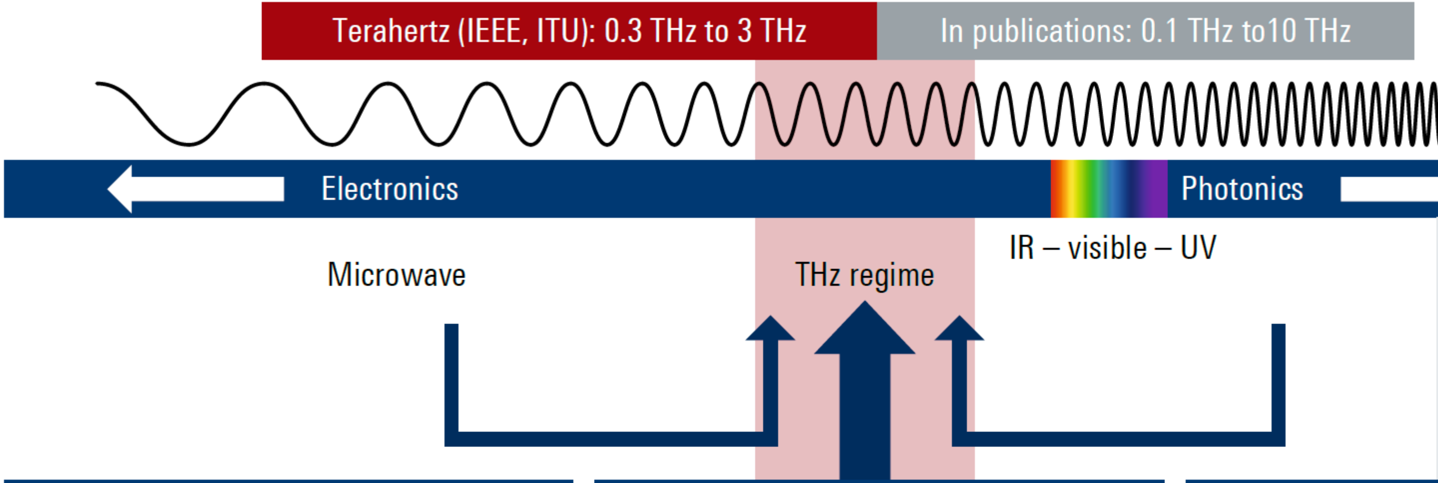
Microwave links: straightforward application of B5G and 6G

E-band (60-90 GHz) extension into

- W-band (75-110 GHz)
- D-band (110-170 GHz)
- (currently 300 GHz mainly in Japan, not limited to microwave links)

Ways to generate THz radiation

From Electronics to Optoelectronics



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

Upconversion: electronic sources

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

Direct THz emission

- Quantum cascade laser (QCL), nonlinear optics, molecular lasers (power OK, limited efficiency, sometimes cryogenic)

Downconversion: optoelectronics

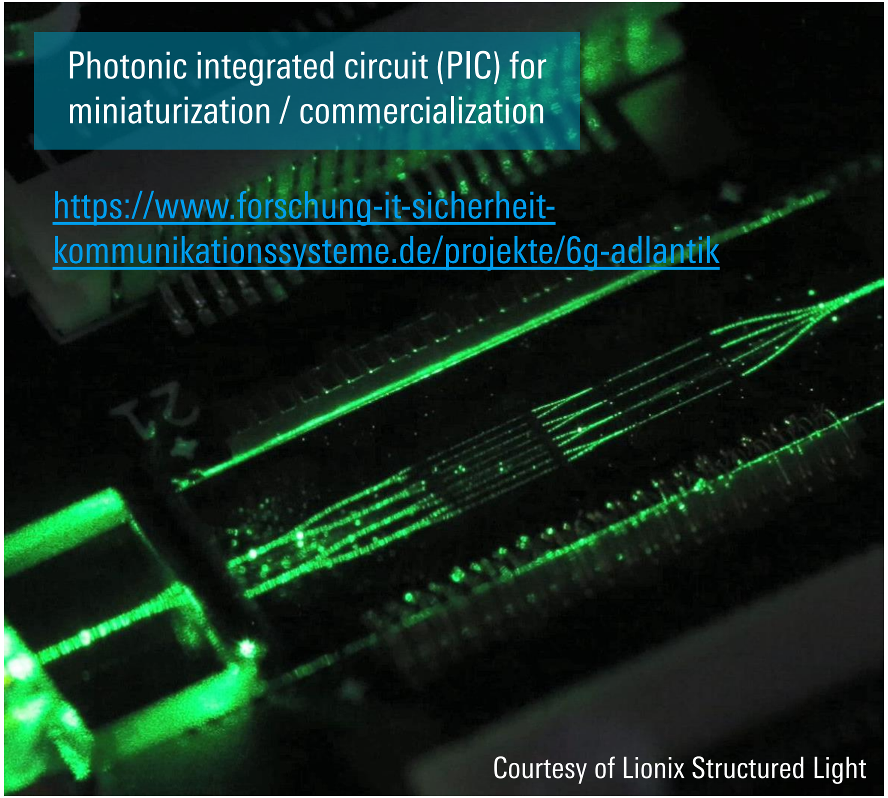
- Photodiodes, photoconductors
- Tunable, room temperature, but power limited, limited efficiency

D band (110 GHz to 170 GHz) signal generation and analysis

R&S®FE170ST frontend transmitter and R&S®FE170SR frontend receiver

The role of photonics in 6G

Photonics could represent to the 21st century, what electronics has meant for the 20th century.



Courtesy of Lionix Structured Light

THz and VLC (6G-ADLANTIK)

- Generation of **THz radiation by optical mixing on a photodiode**
- **VLC (visible light communication) also known as LiFi**: modulation of commercial LEDs, cost-efficient with easy integration into existing infrastructure mainly for line-of-sight indoor applications
- optical generation of microwave oscillators with ultra-low phase noise

All-Photonic networks (APN)

- **Innovative Optical and Wireless Networks Global Forum (IOWN GF)**
- end-to-end optical path between points in the networks with minimal photo-electric conversion to realize **large-capacity, low-latency, and low-energy** consumption infrastructure

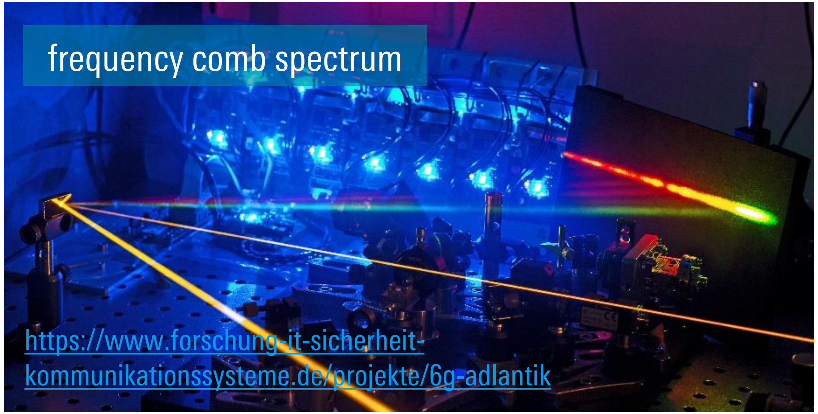
Quantum communication and quantum networks

- **trustworthiness** for ultra-secure and reliable communication
- inherently secure way of **quantum key distribution (QKD)** by exchange of entangled photons (eavesdropping is “measurement”, changes q.state)

6G-ADLANTIK

Photonic generation of THz signals and application for test and measurement.

Bundesministerium
für Bildung
und Forschung



Project coordinator and partner

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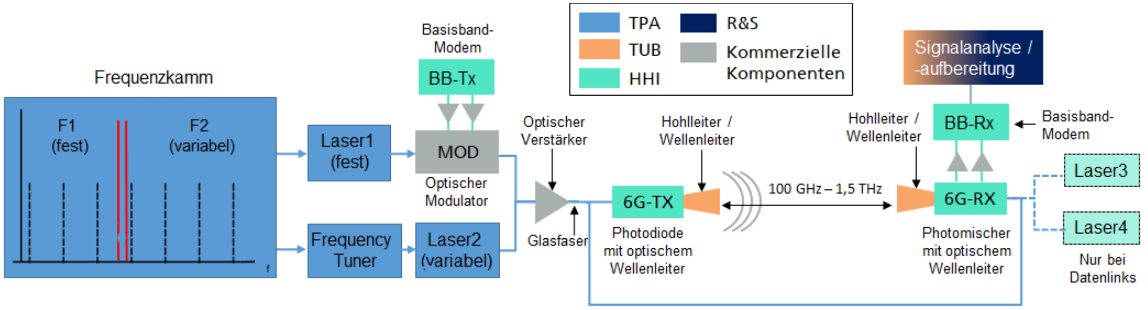
MICROWAVE PHOTONICS

Fraunhofer HHI

SPINNER

TECHNISCHE UNIVERSITÄT BERLIN



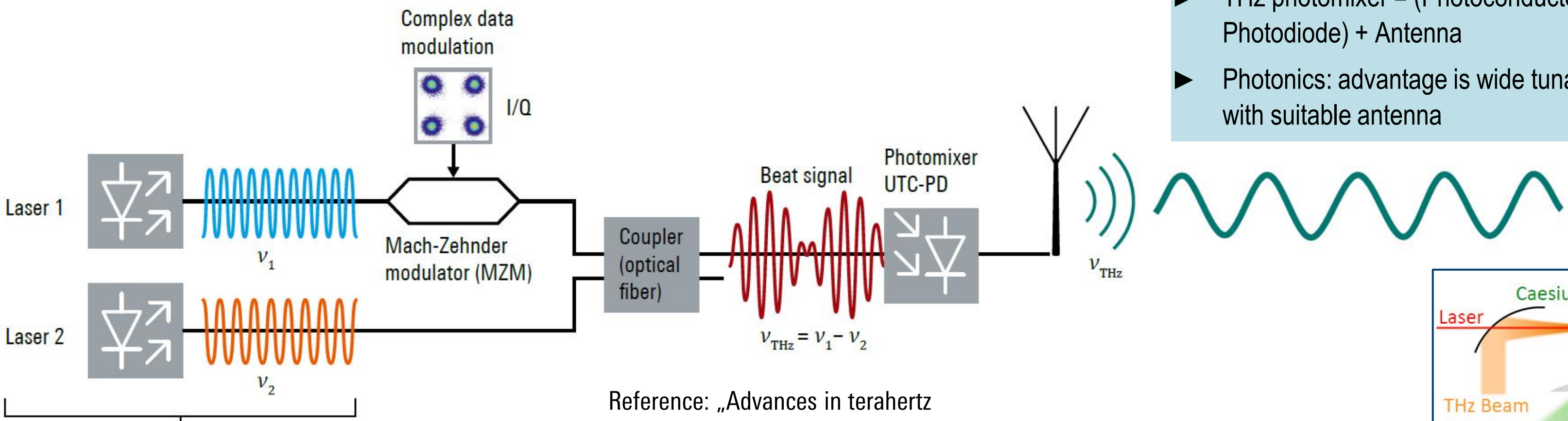
Objective

- Generation of THz radiation by optical mixing on a photodiode
- optical generation of microwave oscillators with ultra-low phase noise
- instrumentation

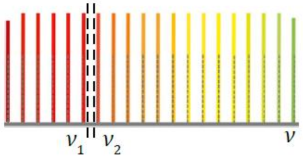
Down-conversion: Optoelectronic THz Generation

Photomixer: unitraveling carrier photodiode (UTC-PD)

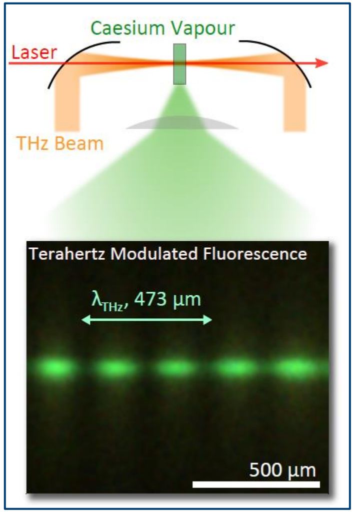
- The photomixer: a quadratic converter
- THz photomixer = (Photoconductor Photodiode) + Antenna
- Photonics: advantage is wide tunability with suitable antenna



Mode locked laser:
laser 1 and laser 2 can be derived from optical frequency comb



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



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

THz waves for communications

300 GHz bi-directional link demonstration over 650 m (2022, THOR project)

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

Phase noise measurement basics

Photonic microwaves with Optical Frequency Combs.

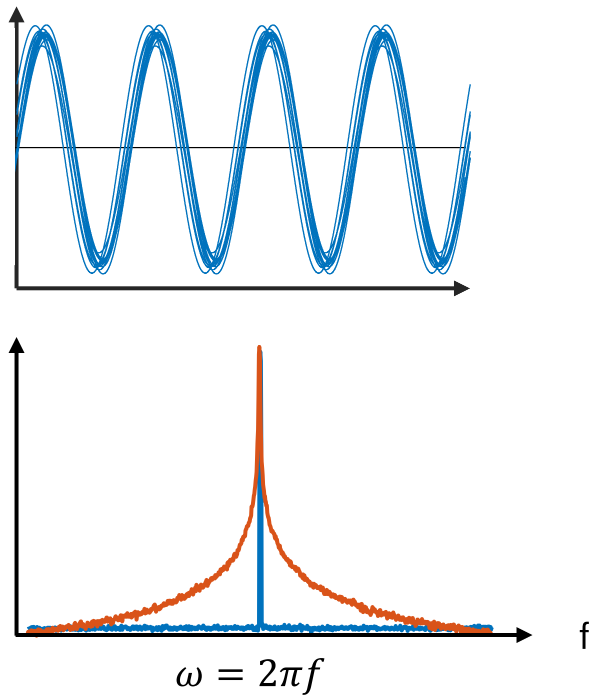
What is phase noise ?

- Phase noise describes short-term variations in the frequency or phase of a signal
  - Short-term → seconds or less
  - Random / unintentional phase modulation

A real (non-ideal) oscillator signal

$$V(t) = A(\boldsymbol{t}) \cdot \cos(\omega t + \phi(\boldsymbol{t}))$$

- Radial frequency "ω" is still constant
- Amplitude "A(t)" is a function of time
- Phase offset "φ(t)" is a function of time
- Creates sidebands in the frequency domain
- In most cases, the effects of phase variations φ(t) are much larger and more important than the effects of amplitude variations A(t)

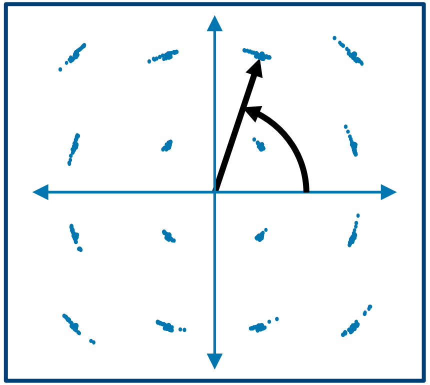


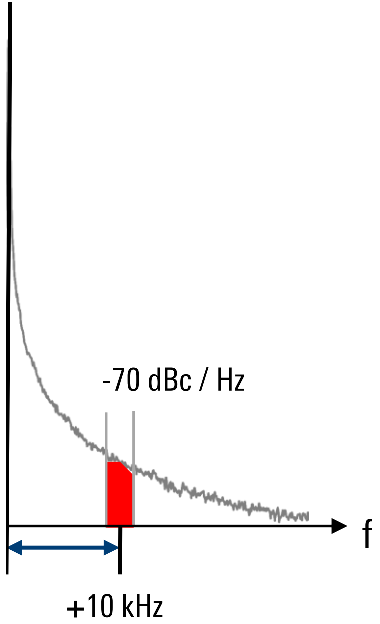
Phase noise measurement basics

Impact on digital modulation in communication systems

Phase noise in communication systems

- Most modern high data-rate systems (e.g. Wi-Fi, LTE, 5GNR, etc.) use some form of phase and amplitude modulation
  - e.g. APSK or QAM
- Modulation often shown as constellation diagram
  - Symbols are unique amplitude / phase pairs
- Phase noise can “rotate” the constellation points
  - Symbols are incorrectly interpreted
  - Increased bit error rate (BER)
  - Modulation quality (phase error, EVM) is degraded by phase noise





Single sideband (SSB) phase noise

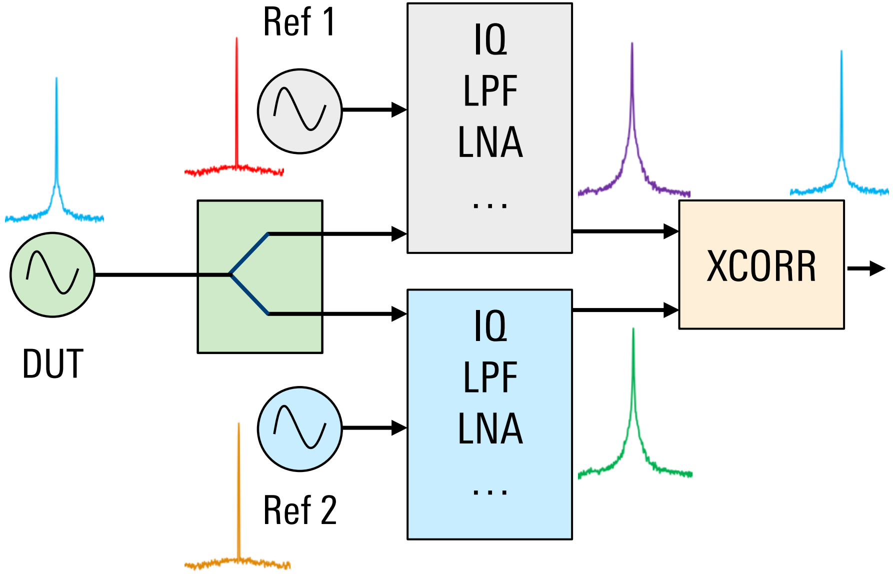
- Phase noise sidebands are usually symmetrical around the carrier
  - Same phase noise at positive or negative offset
- Single sideband (SSB) phase noise
  - phase noise is normally only measured on one side the carrier, upper sideband (positive offsets) is used by convention

Phase noise analyzer
Crosscorrelation method

Phase Noise PN analyzer

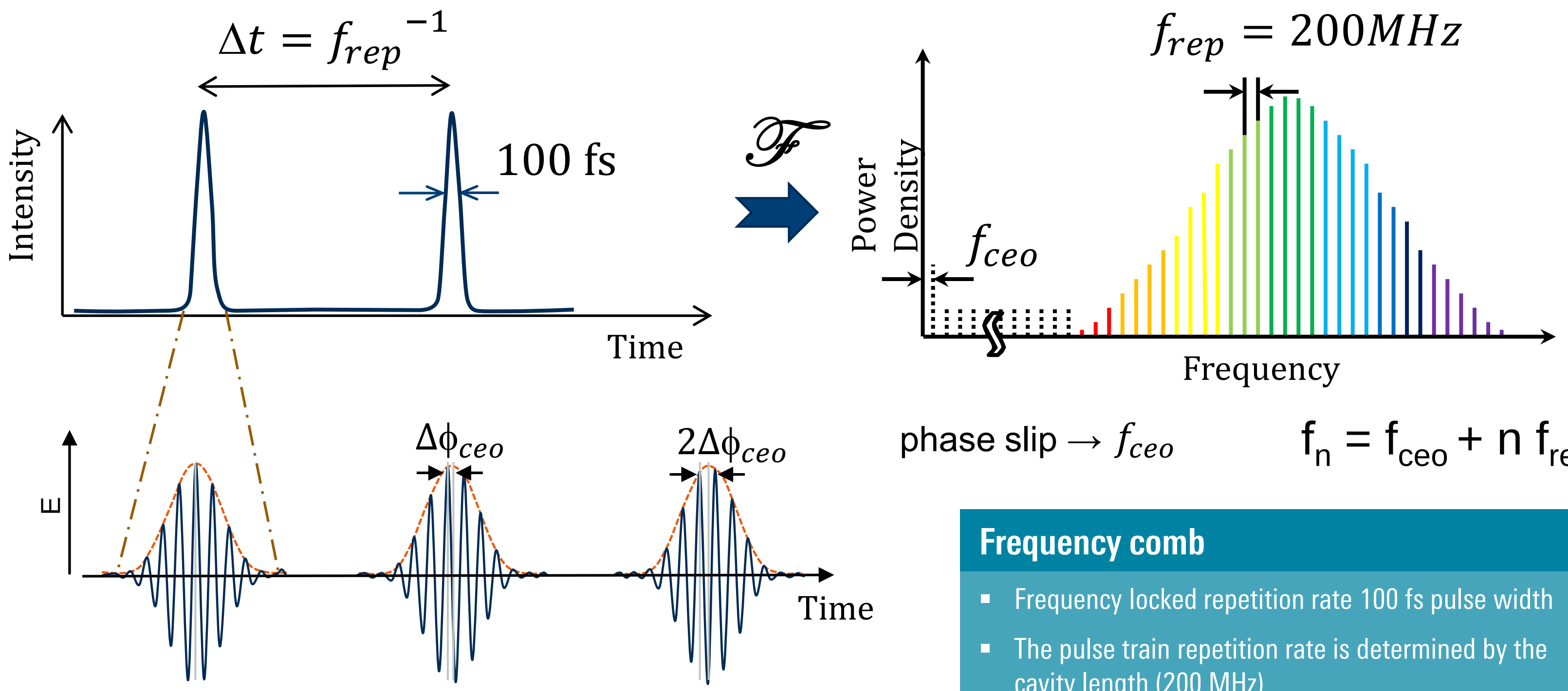
- Measures PN using a digital phase demodulator
- Cross-correlation function
  - Signal is routed through two “identical” paths
  - Each path has slightly different phase noise
  - Cross-correlation function removes instrument-generated phase noise
  - Increasing number of cross correlations increases sensitivity
- Advantages
  - Faster (especially for close-in offsets)
  - Much greater measurement sensitivity

Cross correlation method



Laser-based ultra-low phase noise microwaves sources

Photonic microwaves with Optical Frequency Combs.



phase slip → f_{ceo}

$f_n = f_{ceo} + n\ f_{rep}$

Frequency comb

- Frequency locked repetition rate 100 fs pulse width
- The pulse train repetition rate is determined by the cavity length (200 MHz)

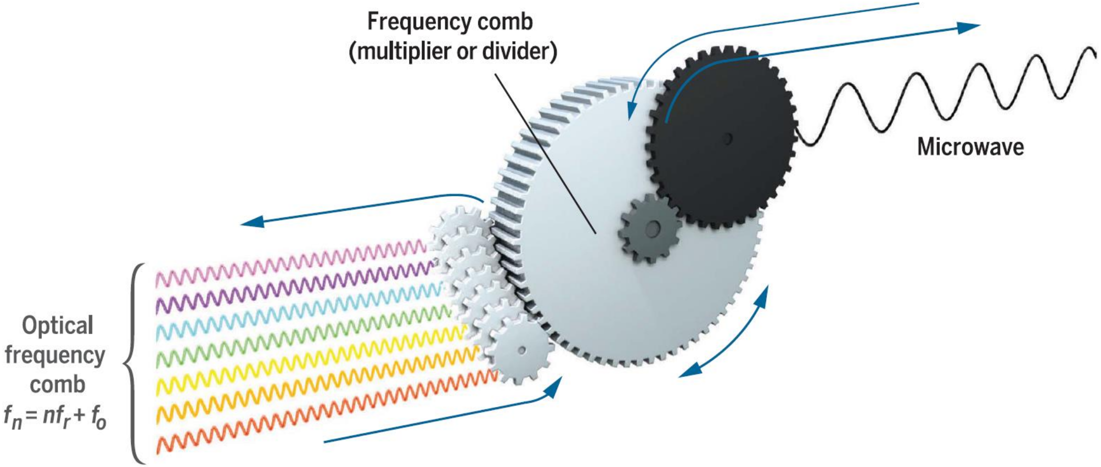
Ultra-low phase noise photonic microwaves sources
based on an optical frequency comb derived from a femtosecond pulsed laser

Frequency comb

- The pulse train repetition rate is determined by the cavity length (mode coupling in mode locked laser)
- Phase coherence of optical is transferred to the microwave regime

Phase calibration by frequency comb

- Fixed phase relationship between frequencies of comb
- Configure comb line spacing
- High speed photo diode with calibrated phase response
- Broadband phase alignment and calibration of electrical test and measurement equipment



Scott A. Diddams, et al., Optical frequency combs: Coherently uniting the electromagnetic spectrum. Science **369**, eaay3676 (2020). DOI: 10.1126/science.aay3676

OAM Orbital Angular Momentum

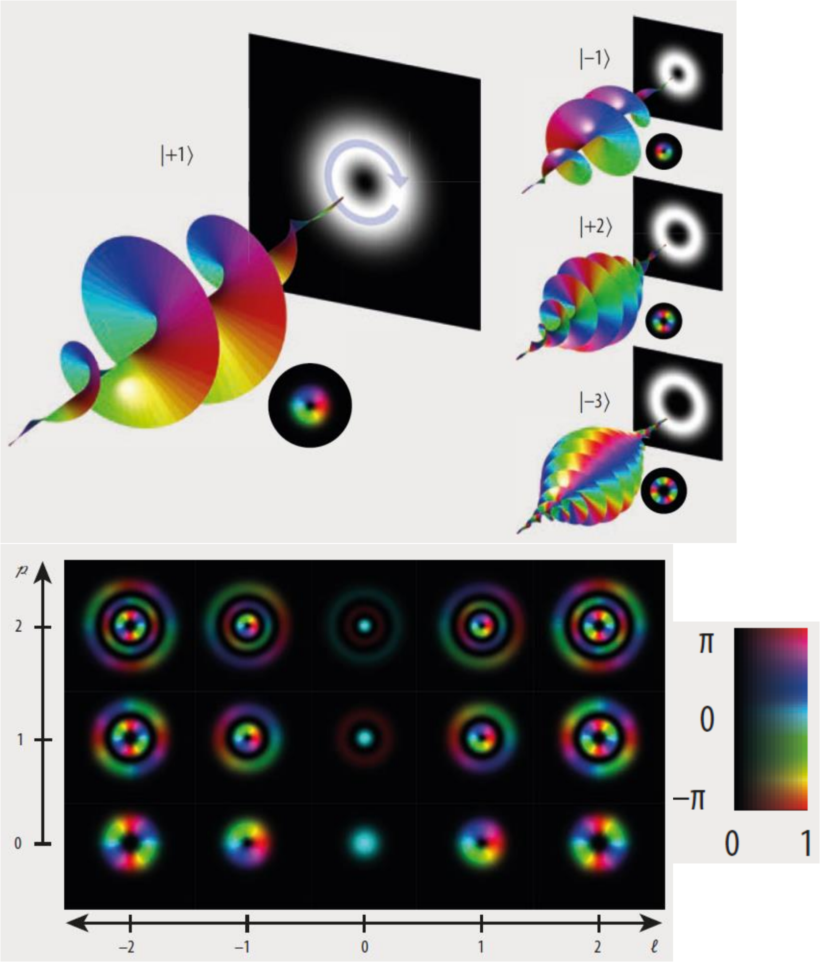
Structured Photons

Structured photons

- What is the meaning of structure / modes for single photons ?
- Vortex phase structure
- Intensity distribution is the probability to detect a photon at a certain location
- Known since only 25 years…

Laguerre Gauss modes (l, p)

- Laguerre Gauss modes in cylindrical coordinates wave character of photon in transverse structure as solution of the wave equation in cavity
- Quantum number angular l and radial p
- No principal difference between optical and radio frequency (only energy different)



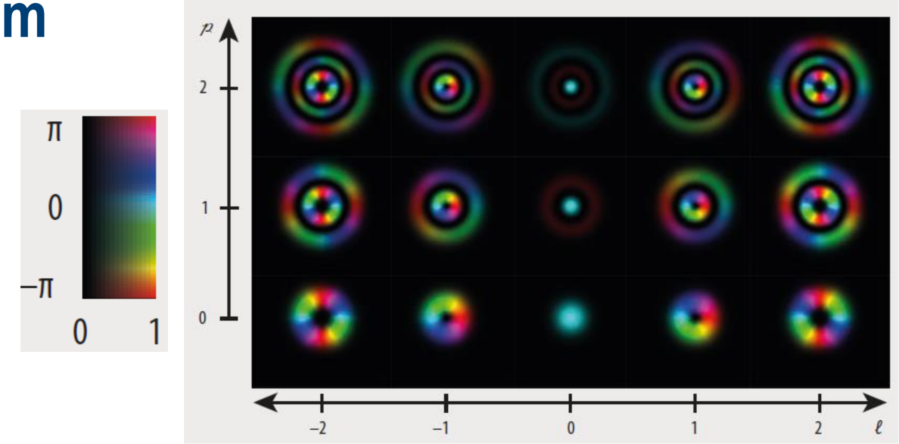
R. Fickler, Physik Journal 22 (2023) No. 2, pp. 29-34

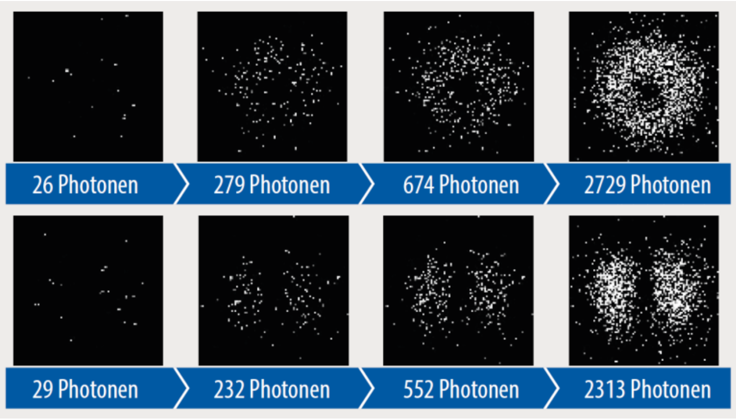
OAM Orbital Angular Momentum

Structured Photons

Single photons with angular momentum

- Single photons can have spatial structure including their properties.
- Structures appear when many detection processes of single photons in the same mode are added on a sensitive camera.
- Superposition states are possible !





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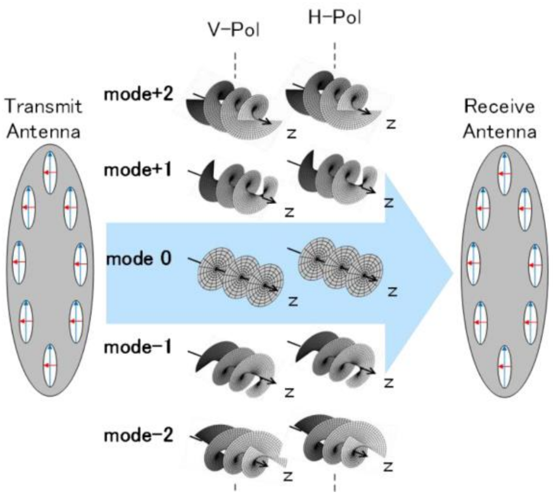
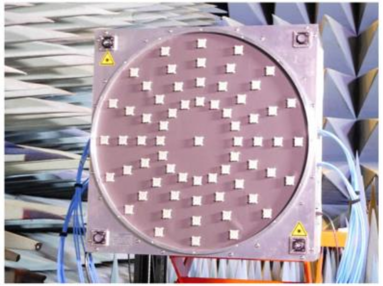
OAM multiplexing technology for communication

Phase shift matrix/unit is needed to form vortex orthogonal electromagnetic waves



https://www.nec.com/en/press/202003/global_20200310_01.html

Yan, Y., Xie, G., Lavery, M. et al. High-capacity millimetre-wave communications with orbital angular momentum multiplexing. Nature Communications 5, 4876 (2014). https://doi.org/10.1038/ncomms5876



NEC

- NEC successfully demonstrates real-time digital OAM (Orbital Angular Momentum) mode multiplexing transmission over 100m in the 150GHz-band for the first time
- 256 QAM x 16 streams multiplexing
- 100 m, 14.8 Gbps in D-band transmission test

NTT

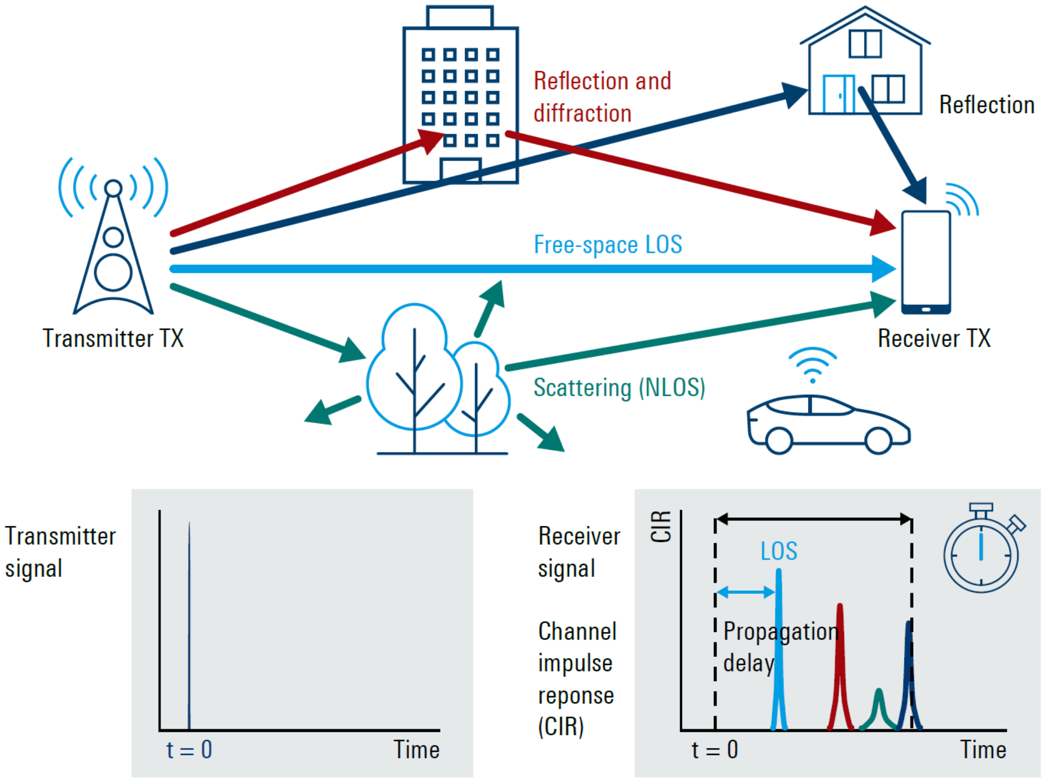
NTT Press Release (2018): “NTT successfully demonstrates 100 Gbps wireless transmission using a new principle (OAM multiplexing) as a world's first”

From channel sounding to channel models for 6G

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

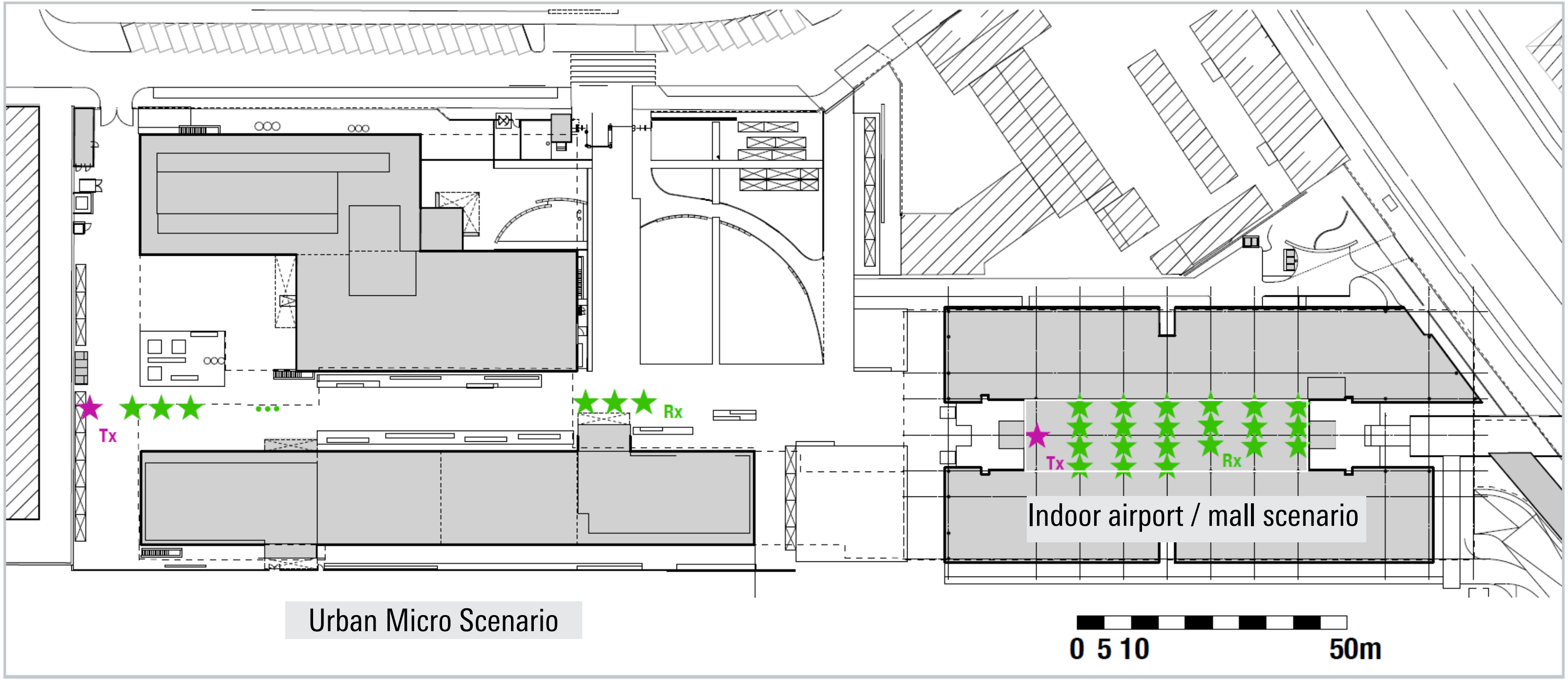
Key concepts:

- Broadband and spatially resolved channel models are the basis for system design, evaluation and optimization.
- There are many open research questions, related to sub-THz system design, like power of multi-path components, sparsity of the channel, choice of beamwidth.
- Deterministic channel models like ray-tracing require calibration and verification.
- We need channel measurements !



Sub-THz channel measurements on the R&S campus

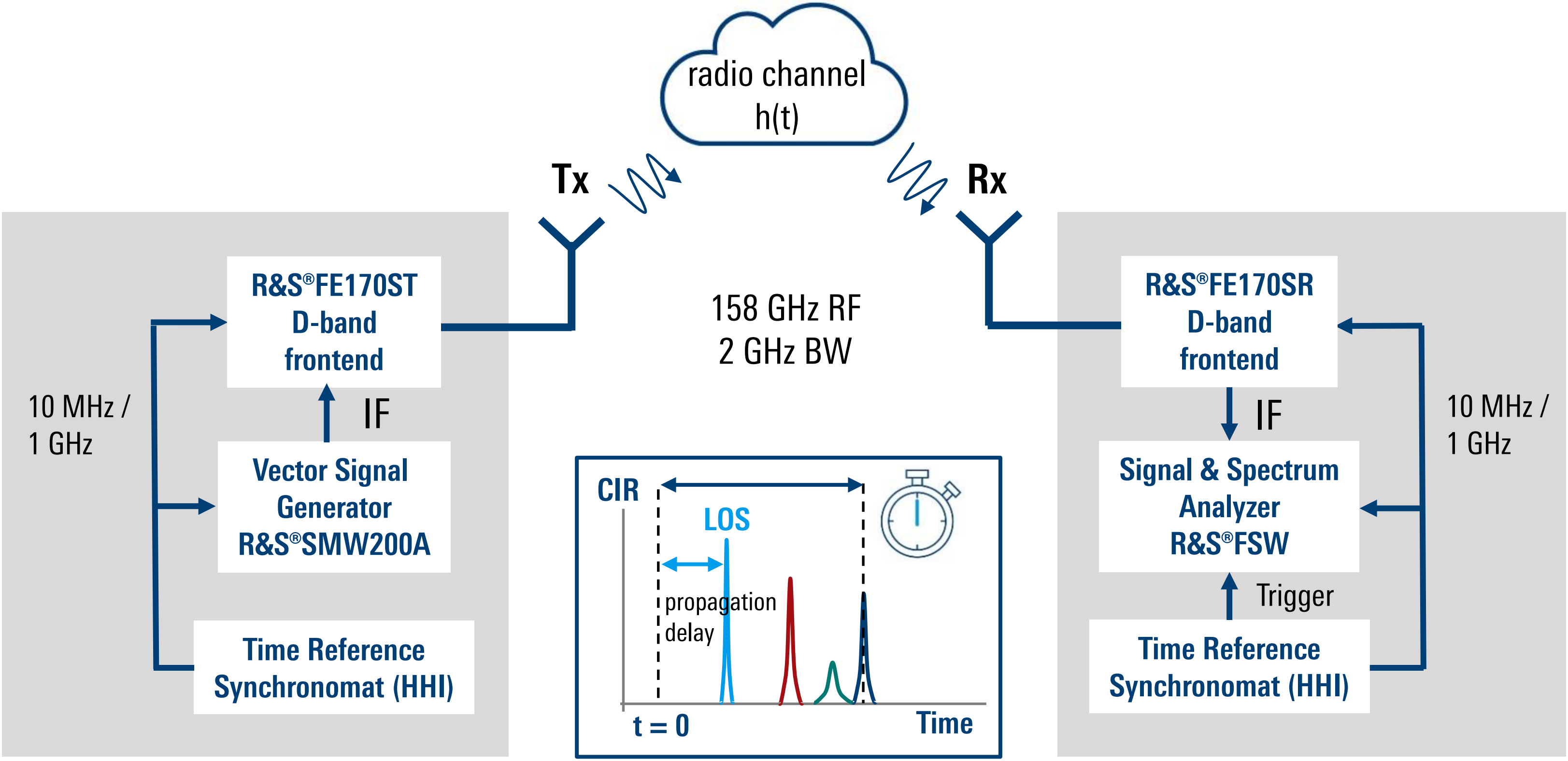
CIR of outdoor and indoor environment at 300 GHz and the D-band (158 GHz)



Antenna heights: 1.5 m at Tx and Rx

Time domain channel sounding setup at 158 GHz

Propagation delay measurement between transmitter and receiver



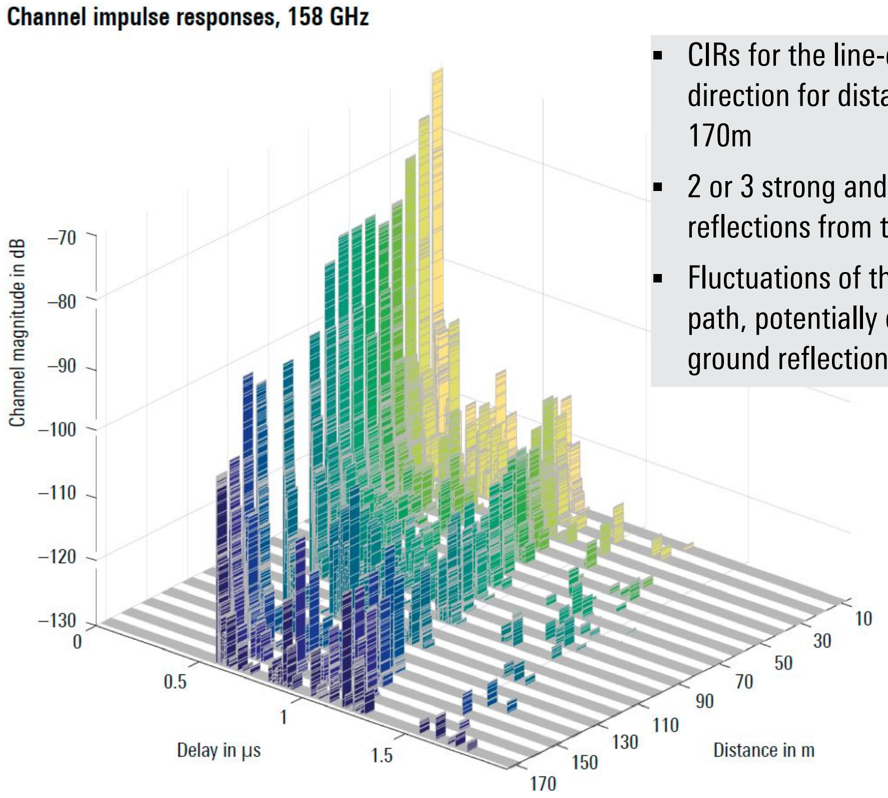
CIR comparison at 158 GHz and 300 GHz

Reference

- W. Keusgen, A. Schultze, M. Peter and T. Eichler
- "Sub-THz Channel Measurements at 158 GHz and 300 GHz in a Street Canyon Environment," presented at the 2022 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit), Grenoble, 2022.
- https://arxiv.org/abs/2203.04404

Large-scale outdoor street canyon scenario measurements

CIRs at 158 GHz with aligned antennas from 10 m to 170 m



- CIRs for the line-of-sight direction for distances up to 170m
- 2 or 3 strong and stationary reflections from the buildings
- Fluctuations of the main path, potentially due to ground reflection

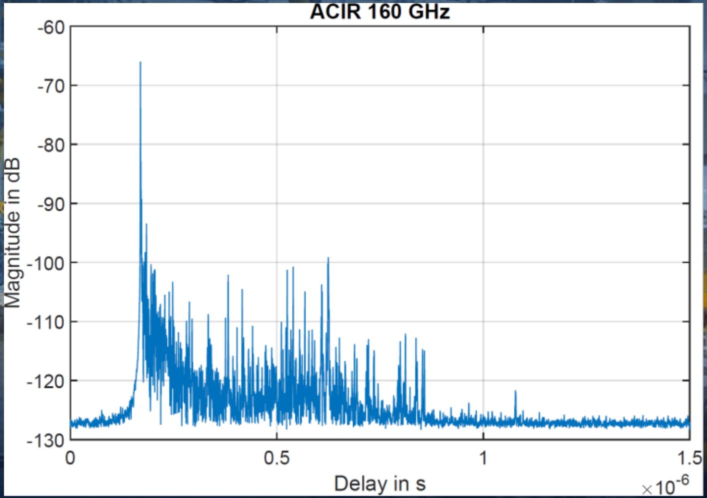
6G D-band industrial channel measurements with HHI

6G channel models in industrial scenarios for 3GPP: production environment measurement campaigns in Memmingen plant (January 2023)

Measurement Campaign at 3.7 GHz, 28 GHz and 160 GHz

„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

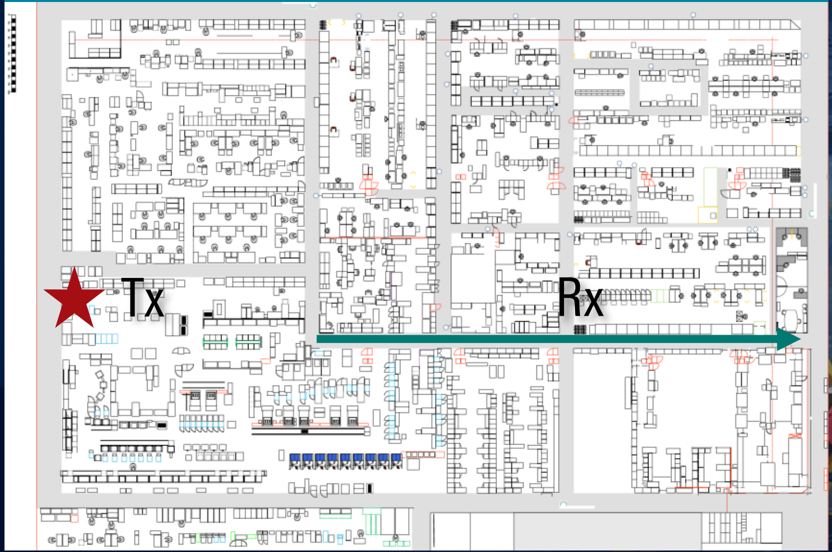
Power Delay Profile



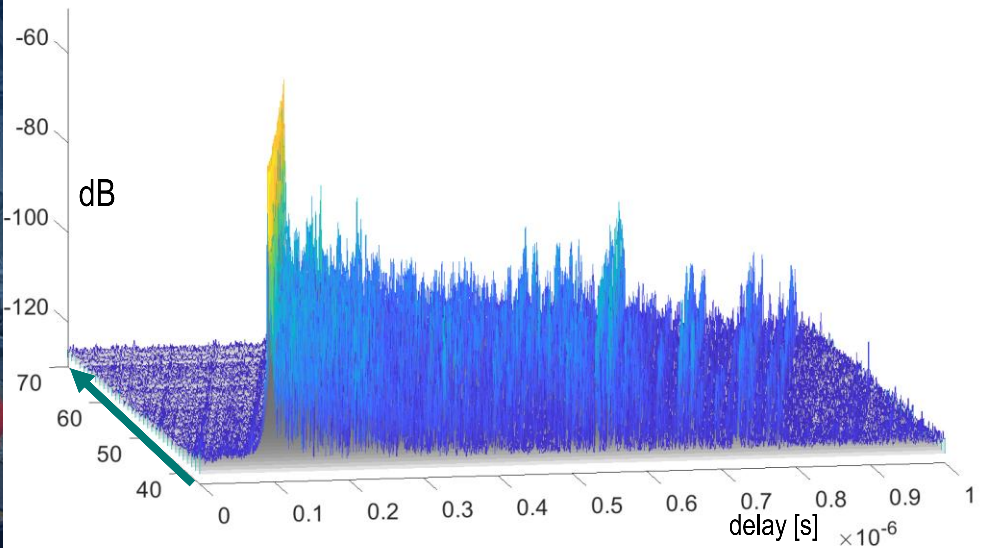
6G D-band industrial channel measurements with HHI

6G channel models in industrial scenarios for 3GPP: production environment measurement campaigns in Memmingen plant (January 2023)

Factory floor plan: Tx and Rx position



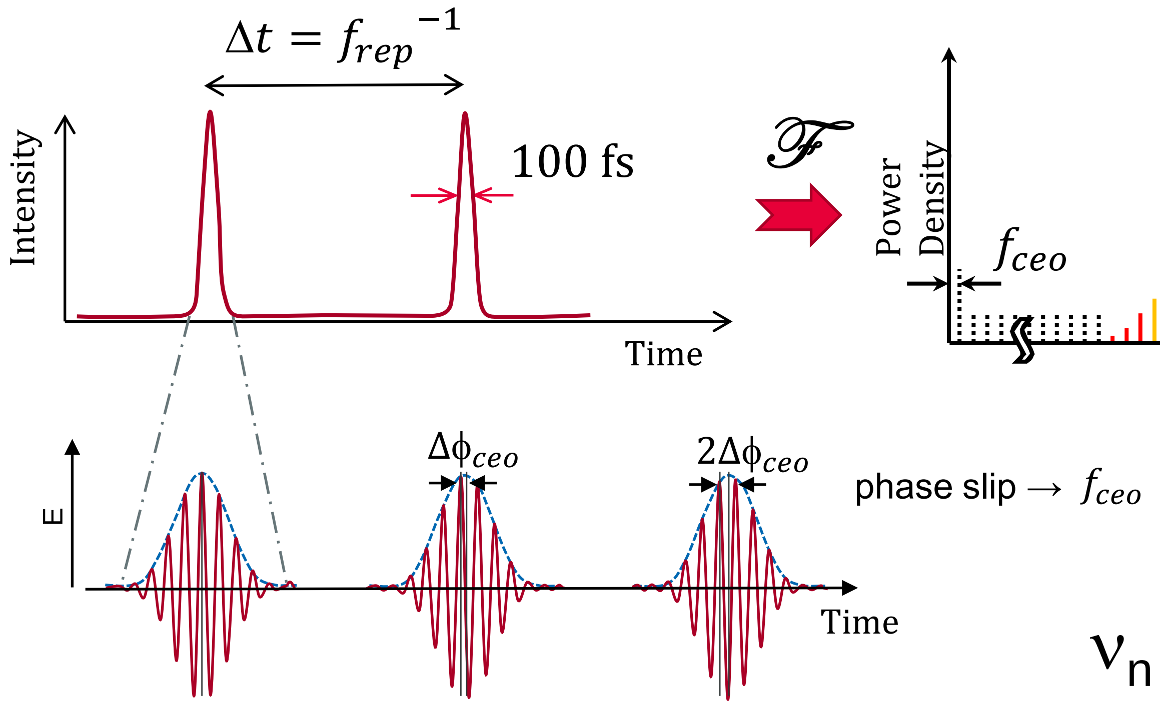
Power delay profile CIR 160 GHz (mainly LOS path)



Demo

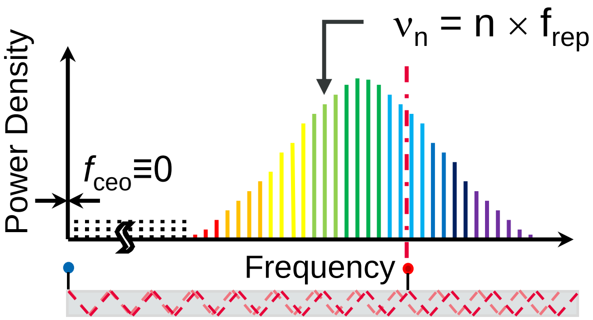
Phase noise measurement of an ultra-stable microwave system based on optical comb frequency difference generation

Frequency comb



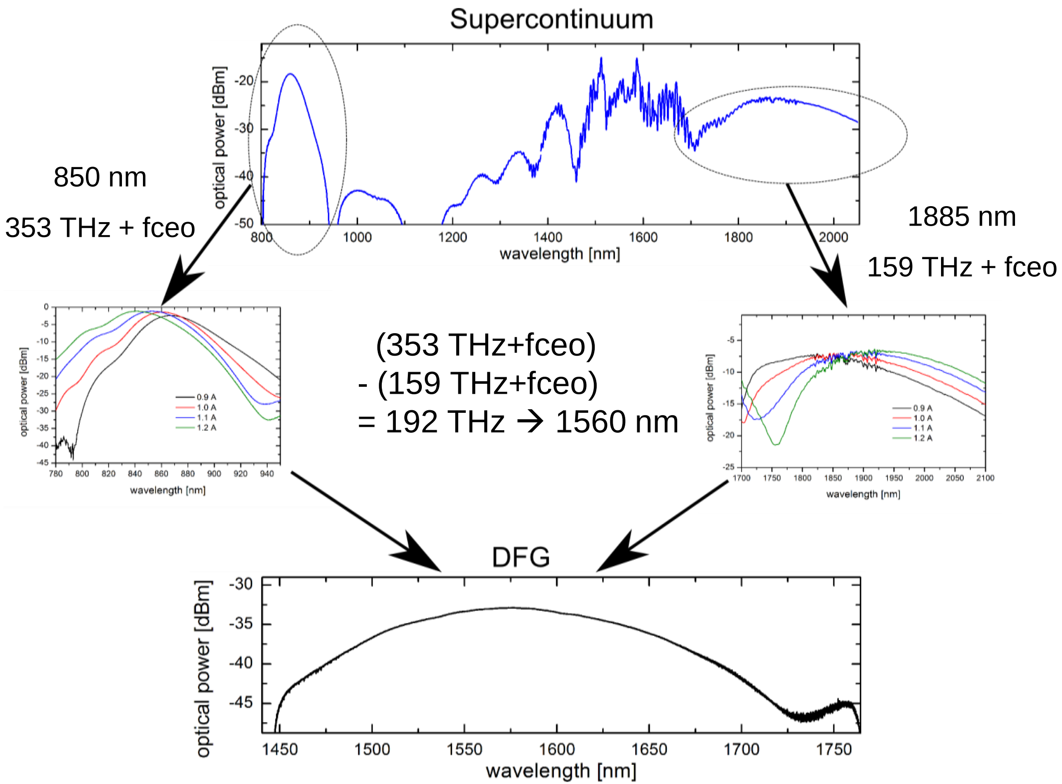
$$\nu_n = f_{ceo} + n\, f_{rep}$$

Frequency Comb based in Difference-Frequency Generation

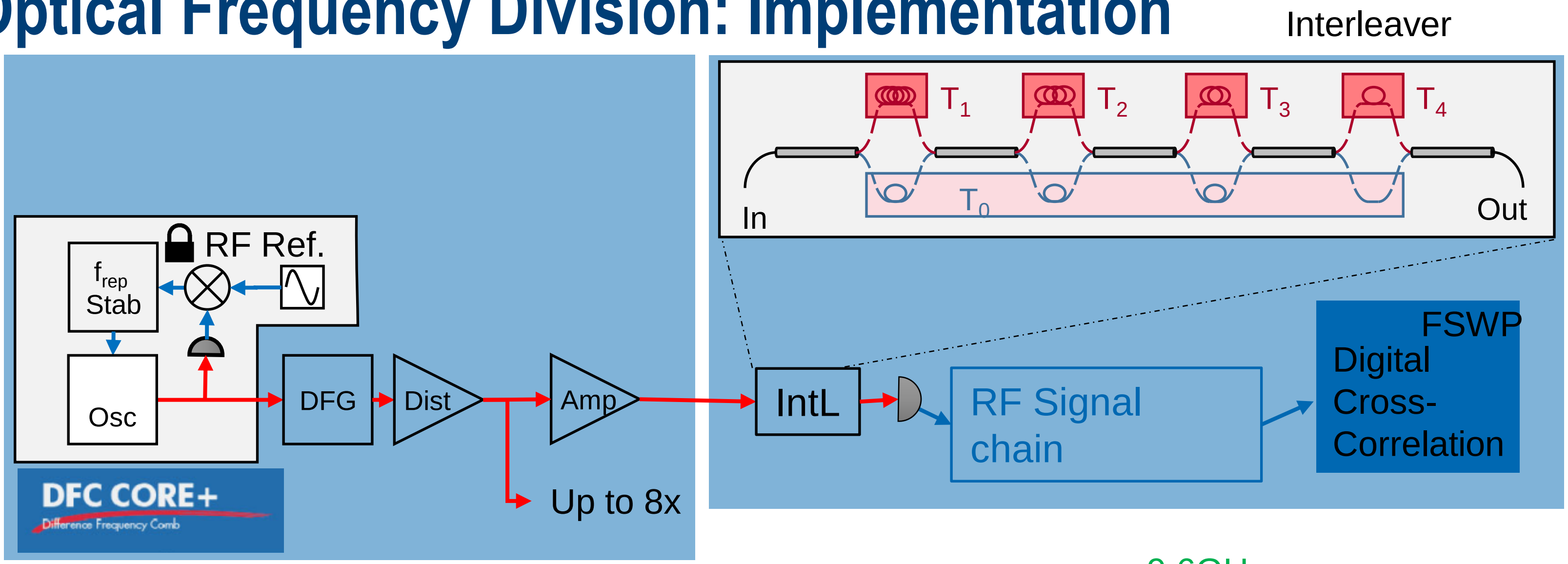


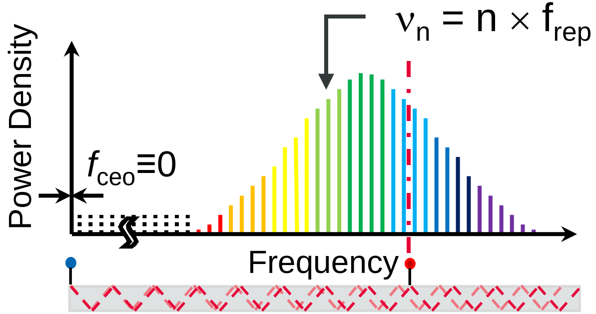
$$\nu_n = \cancel{f_{CEO}} + n\, f_{rep}$$

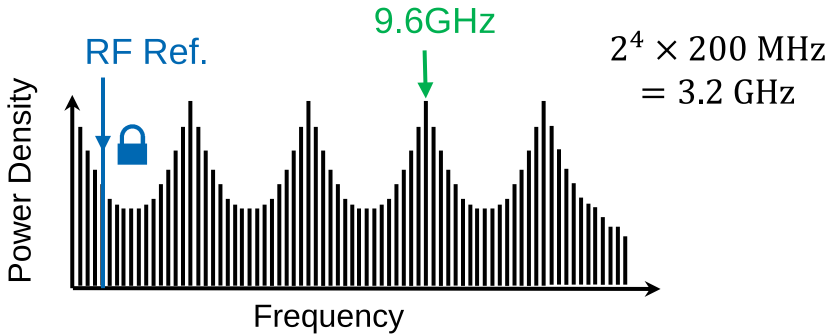
DFG: $f_{CEO} \equiv 0$



Optical Frequency Division: Implementation







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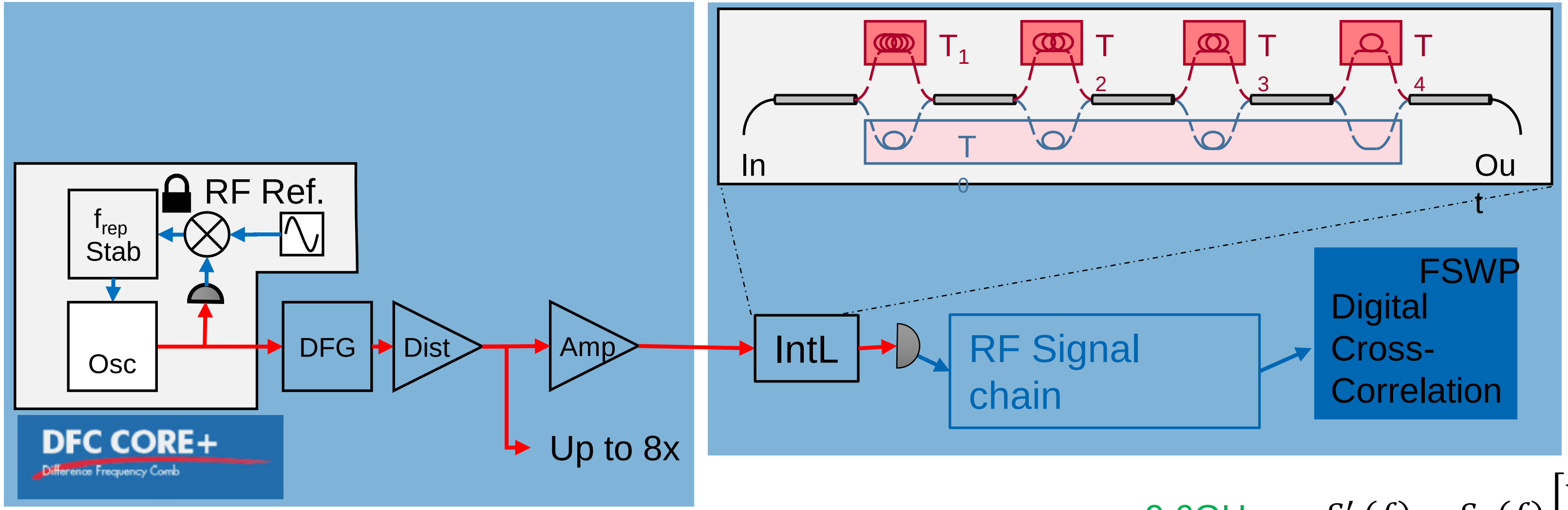
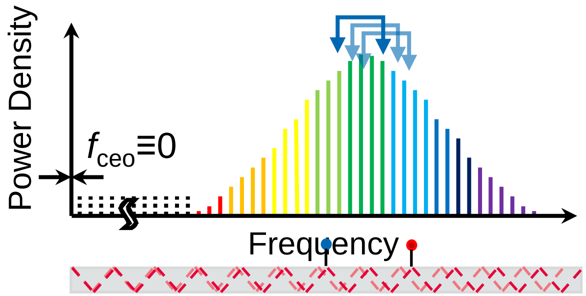
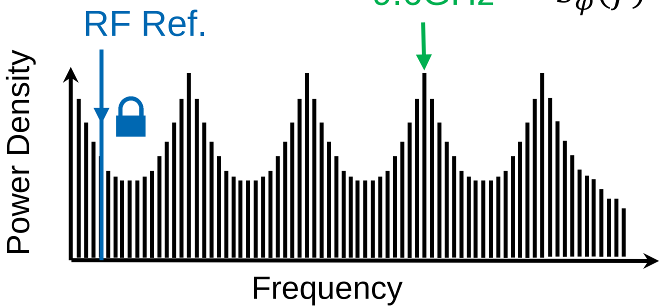
Optical Frequency Division: Implementation







$$S'_\varphi(f) = S_\varphi(f)\left[\frac{\nu'_0}{\nu_0}\right]^2$$

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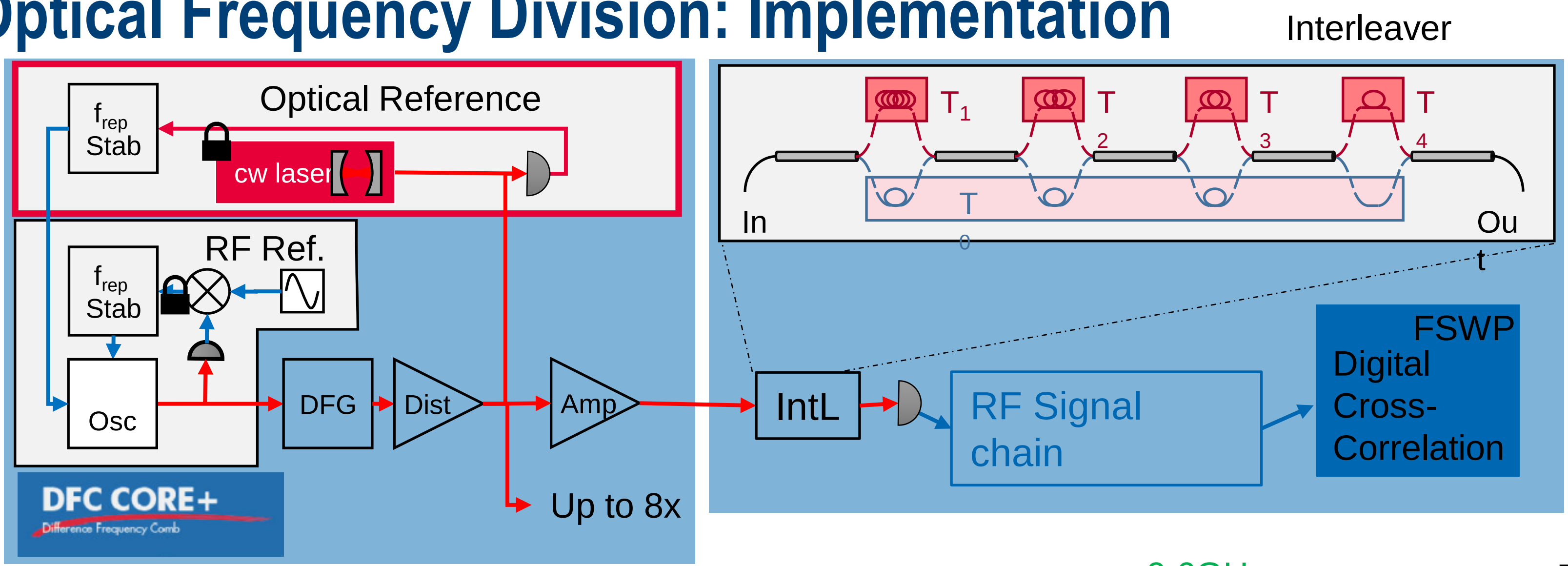
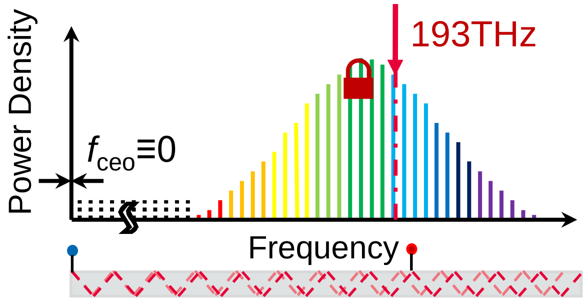
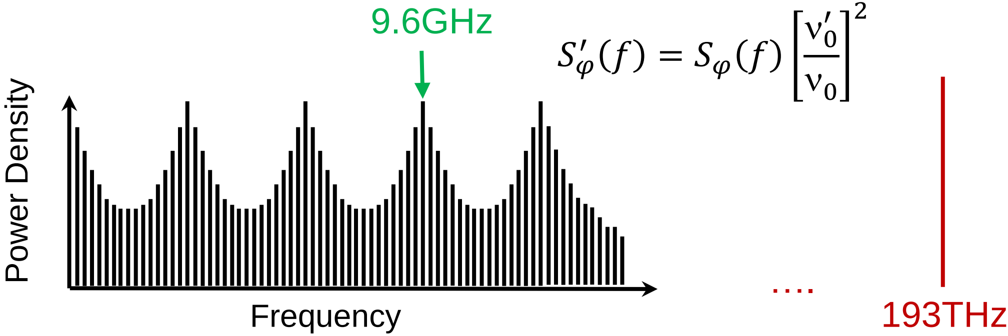
Optical Frequency Division: Implementation







$$S'_\varphi(f) = S_\varphi(f)\left[\frac{\nu'_0}{\nu_0}\right]^2$$

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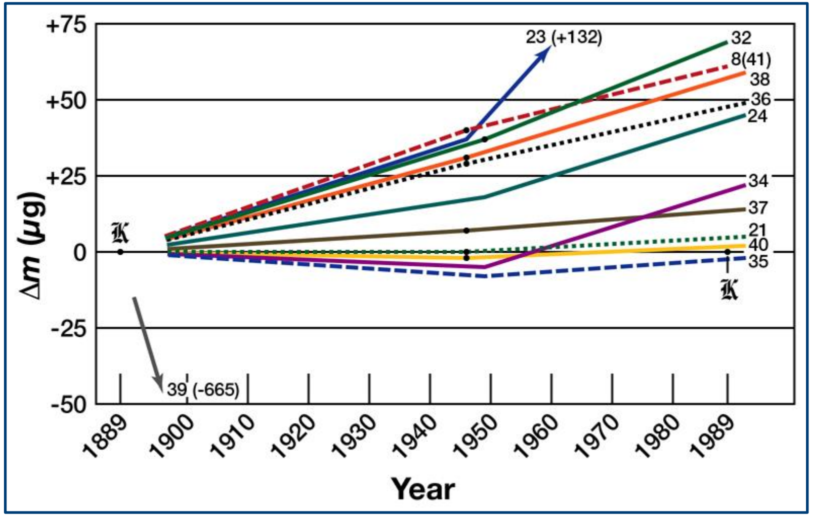
Outlook

The new SI metric system based on fundamental constants

The new kilogram “defined by photonics” (2019)

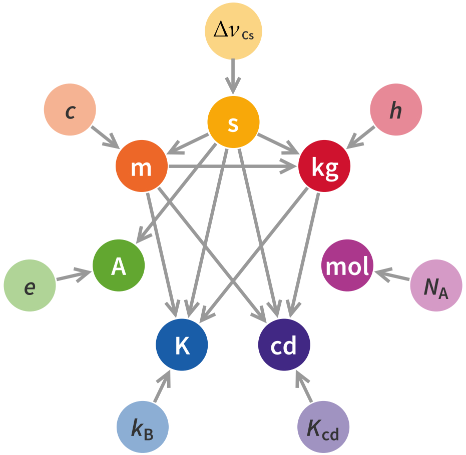
Copy of the original kilogram („Le grand K“, Paris 1889) at the PTB (German National Metrology Institute): 90% platinum, 10% iridium.

Historic mass drift of the various copies of the „urkilogram“.
„The kilogram didn‘t behave well !“



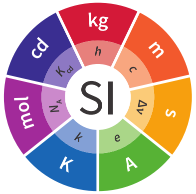
Mass drift over time of national prototypes K21–K40, plus two of the international prototype's sister copies: K32 and K8(41). All mass changes are relative to the IPK.

Re-definition of the kilogram via Planck’s constant
$h = 6.626\,070\,15 \times 10^{-34}$ kg m^2/s

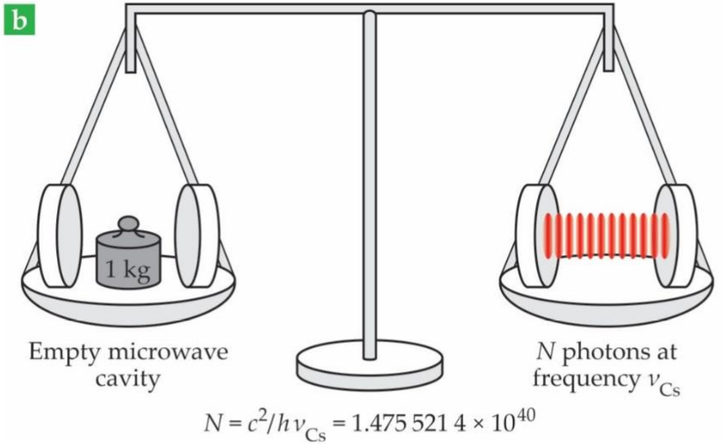


The new SI metric system based on fundamental constants

The new kilogram “defined by photonics” (2019)



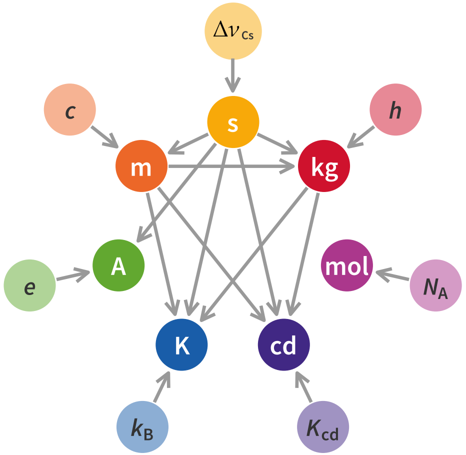
Copy of the original kilogram („Le grand K“, Paris 1889) at the PTB (German National Metrology Institute): 90% platinum, 10% iridium.



The new kilogram's mass corresponds to the energy of 1.4755214×10^{40} photons that are oscillating at the same frequencies as the Cs^{133} atoms used in atomic clocks.

Wolfgang Ketterle: „The new kilogram“
https://www.youtube.com/watch?v=KBZD3tFny_E
Physics Today 73, 5, 32 (2020)

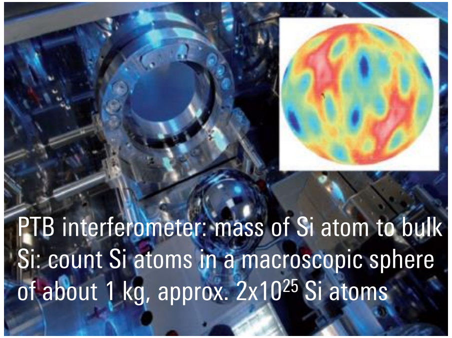
Planck’s constant
$h = 6.626\,070\,15 \times 10^{-34}$ kg m^2/s



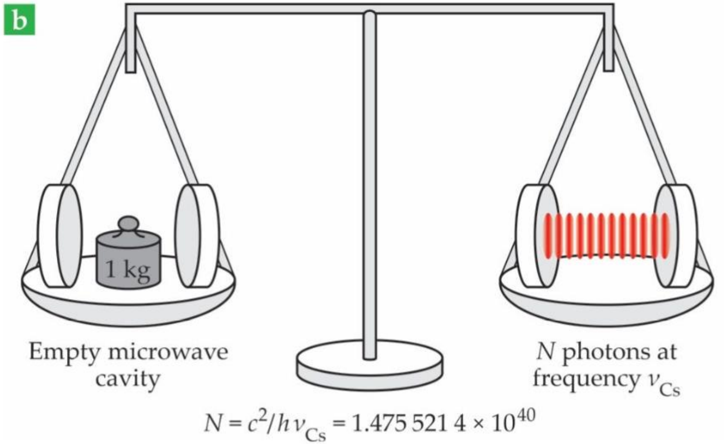
The new SI metric system based on fundamental constants

The new kilogram "defined by photonics" (2019)

PTB: monocrystalline Slicon (Si) sphere



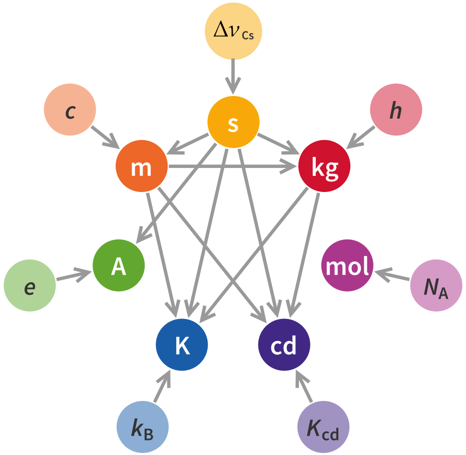
PTB interferometer: mass of Si atom to bulk Si: count Si atoms in a macroscopic sphere of about 1 kg, approx. 2×10^{25} Si atoms



The new kilogram's mass corresponds to the energy of 1.4755214×10^{40} photons that are oscillating at the same frequencies as the Cs^{133} atoms used in atomic clocks.

The better the measurement techniques become, the more precise the realization of the macroscopic kg will be.

Planck's constant
$h = 6.626\,070\,15 \times 10^{-34}$ kg m^2/s



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Find out more

www.rohde-schwarz.com/wireless/6G

Thank you !

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