

Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Introduction to the Horizon 2020 EU-Japan Project ThoR

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Re: n/a

Abstract: This presentation introduces the EU-Japan project ThoR, which works on demonstration of 300 GHz backhaul/fronthaul links, which are in pars based on IEEE Std. 802.15.3d

Purpose: Information of the Technical Advisory Group THz

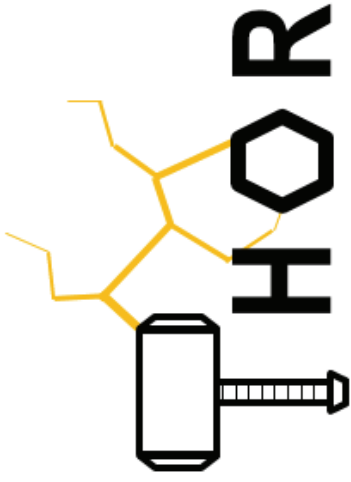
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Introduction to the Horizon 2020 EU-Japan Project ThoR

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Tetsuya Kawanishi, Waseda University, Japan
(Japan Coordinator ThoR)



This project is co-funded by



Horizon 2020



National Institute of
Information and
Communications Technology

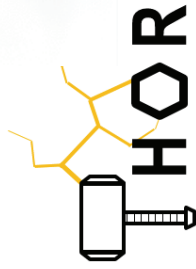
ThoR

THz end-to-end wireless systems supporting ultra-high data Rate applications

Project overview

Outline

1. Introduction to ThoR
2. ThoR approach
3. Hardware
4. THz aspects
5. Summary and expected outputs



ThoR consortium

This **EU-Japan project** is funded by the European Union and the National Institute of Information and Communications Technology (NICT), Japan



Horizon 2020



The consortium unites **12 partners** from ...

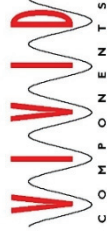
- **Academia, Research**



University of Stuttgart
Germany

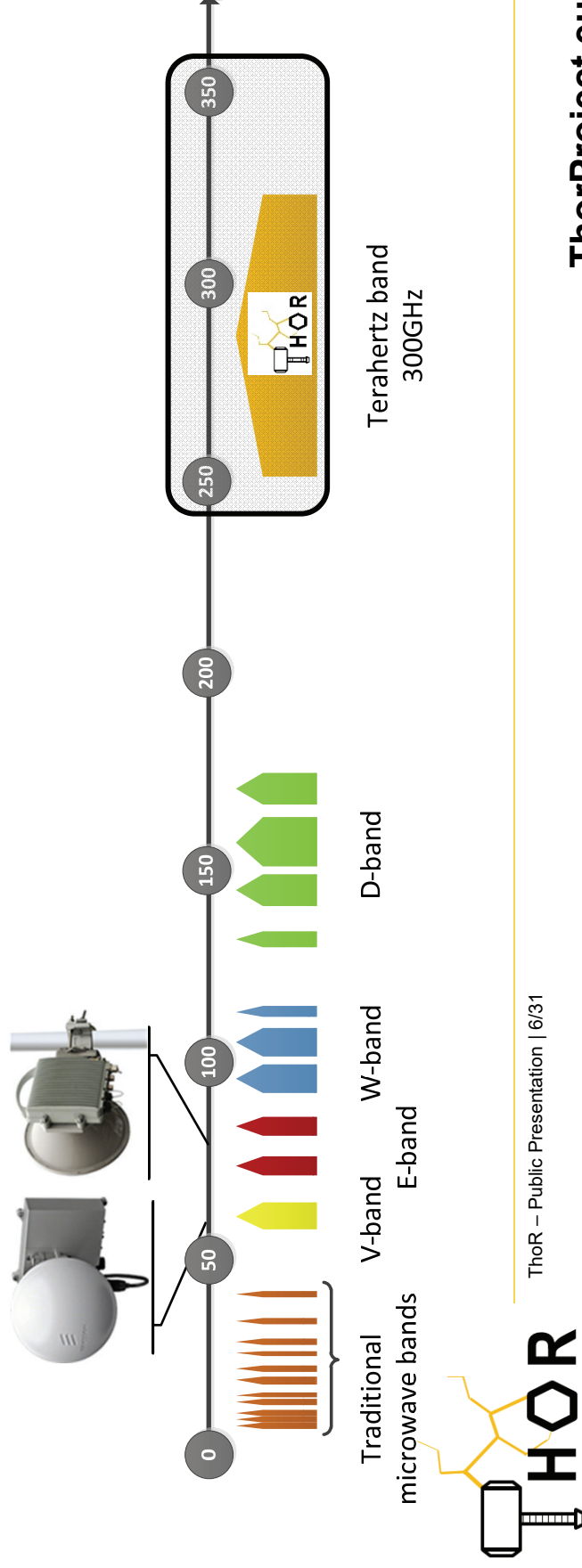


- **and Industry**



The need for Terahertz wireless transport links

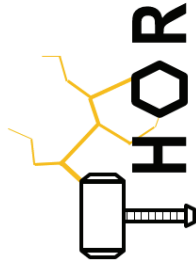
- 5G access networks are already approaching data rate requirements of several Tbps/km²
- Beyond 5G (B5G) networks are expected to ramp this even further
 - New applications and increased uptake
- Expected extension of wireless transport links to W- and D-band only provide mid-term alleviation
- The sub-mm-wave band beyond 300 GHz offers huge bandwidths in a spectral region without specific allocation made yet.
- For the first time, hardware is becoming available to exploit this potential



State-of-the-art for ~300 GHz wireless communication links

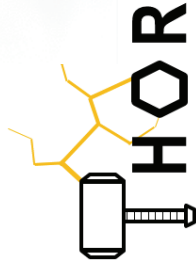
	Data rate / Gbps	Distance / m	Frequency / GHz	Modulation	
1	64	850	240		• High gain parabolic antenna • Offline DSP • Fully monolithic integrated circuit technology
2	100	20	240		• Compact antenna with moderate gain • Photonic Tx with electronic Rx
3	32	25	300	16QAM	• Uni-travelling-carrier (UTC) photodiodes

1. I. Kallfass, F. Boes et al. "64 Gbit/s Transmission over 850 m fixed wireless link at 240 GHz carrier frequency," *J. Infrared Milli. Terahertz Waves* **36**, pp. 221-233 (2015)
2. O. S. Koenig, D. Lopez-Diaz et al., "Wireless sub-THz communication system with high data rate," *Nature Photonics* **7**, pp. 977-981 (2013).
3. Nagatsuma, G. Ducoumau, "Advances in terahertz communications accelerated by photonics," *Nature Photonics*, **10**, pp. 371-379 (2016).



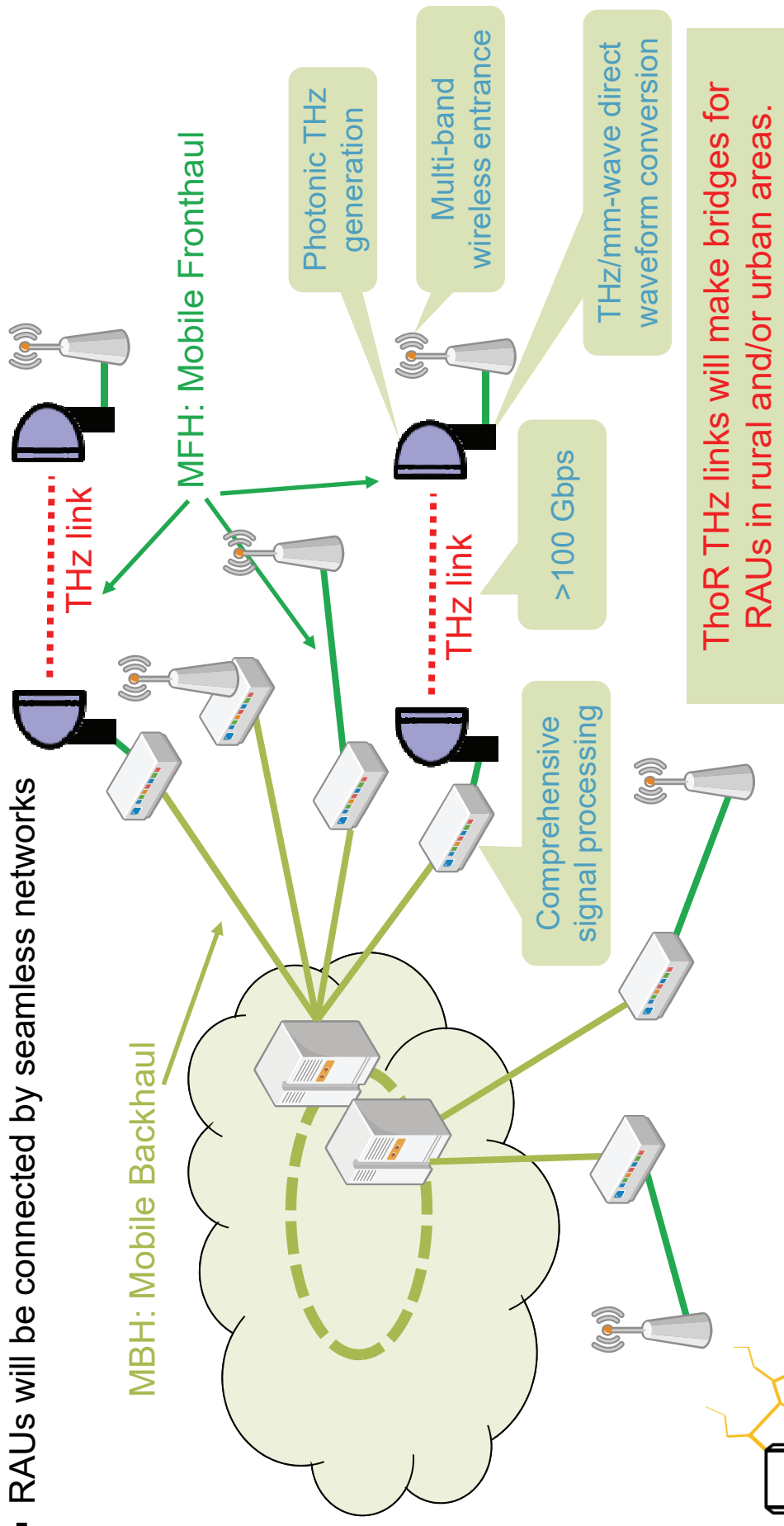
Outline

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- 2. ThoR approach**
3. Hardware components
4. Overall system aspects
5. Summary and expected outputs

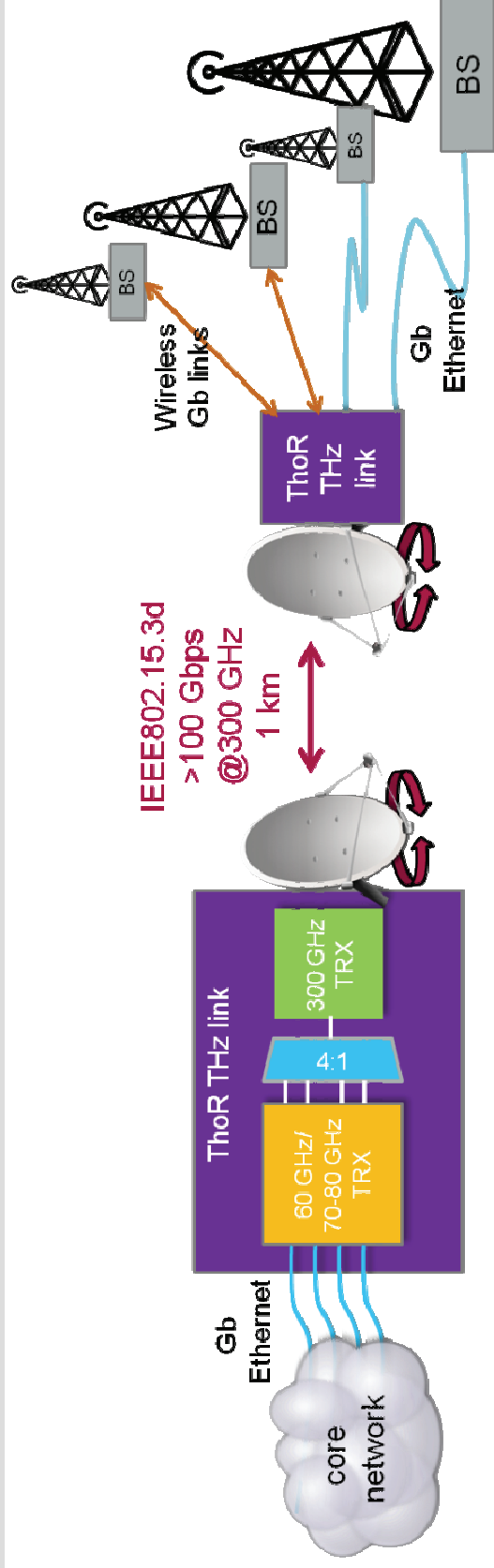


Concept of THz-optical seamless networks

- Beyond 5G systems will have huge numbers of Remote Antenna Units (RAUs)
- Number of RAUs may be larger than number of users
- RAUs will be connected by seamless networks



ThoR approach: capability of 300 GHz backhaul/ fronthaul links



Key Enabling Technologies (KETs)

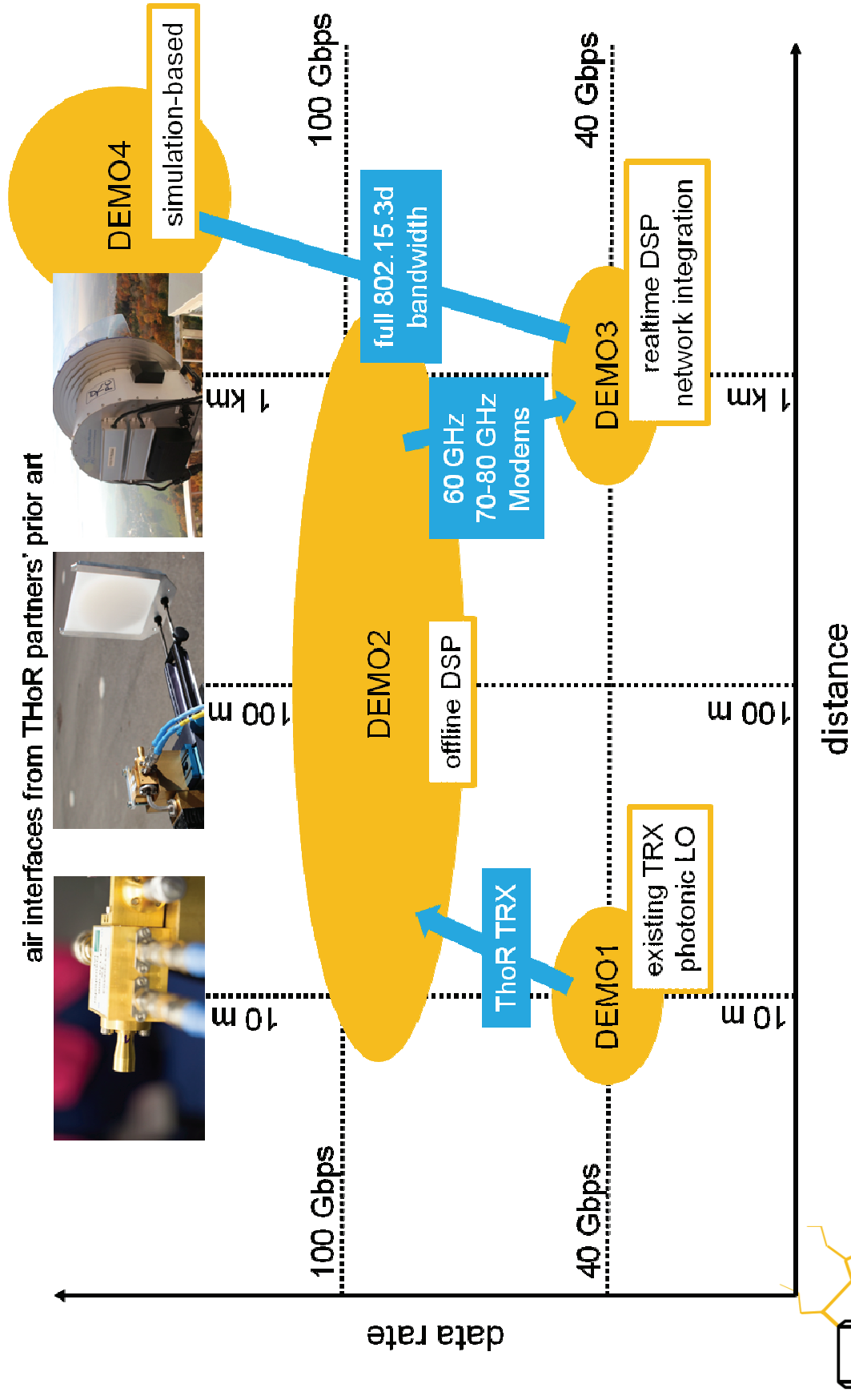
- 1-Photonics-based LO
- 2-Electronic THz amplifier and up-converter
- 3-High Power THz TWTA
- 4-Electronic THz receiver
- 5-Digital baseband & networking interface
- 6-Spectrum regulation and interference mitigation

Key Performance indicators (KPIs)

- 1-Transmitter linearity, bandwidth & output power
- 2-Spectral purity of photonic THz LO
- 3-Bandwidth, noise & linearity in the receiver
- 4-Real-time data rate processing capability
- 5-Spectral efficiency (bit/s/Hz)
- 6-System capacity (Gbps×km)

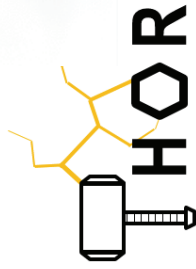


ThoR demonstration concept



Outline

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Integration of complementary hardware components

- The ThOR hardware demonstrators build on components brought into the project based on partner's previous work:
 - Digital baseband & networking interface (Siklu, HRCP)
 - Photonics-based LO (Université de Lille)
 - Electronic THz amplifier and up-converter (Fraunhofer IAF/Universität Stuttgart)
 - High Power THz TWTA (NEC)
 - Electronic THz receiver (Fraunhofer IAF/Universität Stuttgart)
- Integration and demonstration
 - Waseda University will lead the effort to integrate the hardware components from EU and Japan
 - Deutsche Telekom will lead the demonstration with emulated live data

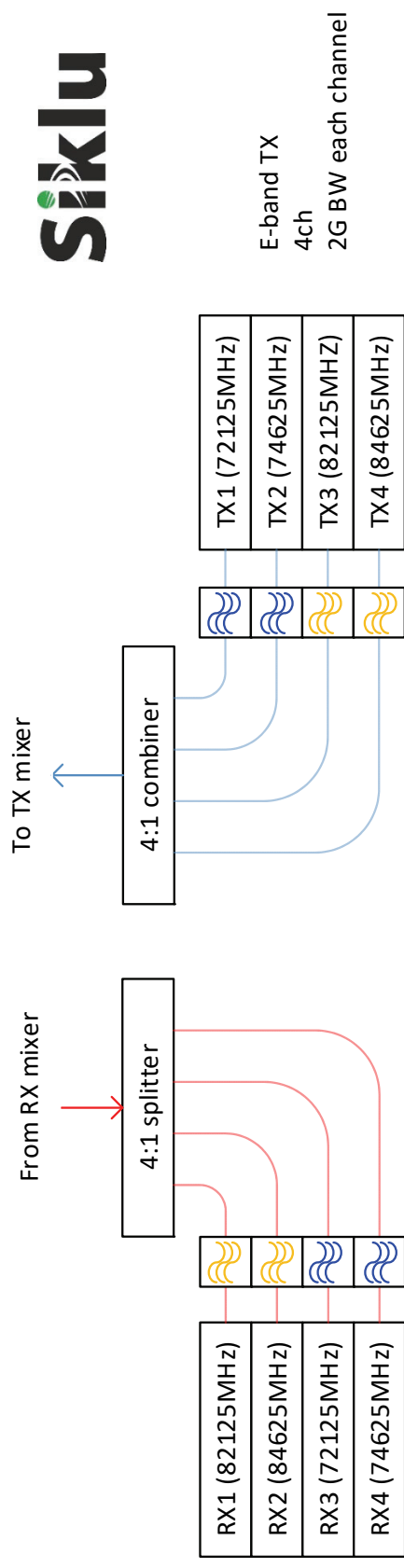


WASEDA University
早稲田大学



Network Connection and basedband processing

Option 1: IF section at E-band for Terahertz P2P link



Siklu

- Frequency division duplex (FDD) operation enables placing based on E-band IF
 - Plenty of spectrum
 - Availability of mature components to construct a low-cost up/down converter
 - ~10 Gbps FDD throughput per up/down converter pair
- Use 4:1 splitter/combiner to aggregate four different channels
 - Tx and Rx channels use a different combiner/splitter
- Aggregation principle may be extended to add further channels for higher throughput
- Flexible cost/performance trade-off



Network Connection and Basedband processing

Option 2: IF section at V-band for Terahertz P2P link

- The 300 GHz Standard IEEE 802.15.3d is based Std. IEEE 802.15.3-2016 and the MAC as well as Modulation and Coding schemes are the same as IEEE 802.15.3e-2017
- Partner HRCP provides IEEE 802.15.3e-2017 chipsets allowing to provide the IF section at V-Band
- Enables to demonstrate that IEEE 802.15.3 protocol is working for 300 GHz Backhaul/Fronthaul links



IEEE STANDARDS ASSOCIATION	IEEE
IEEE Standard for High Data Rate Wireless Multi-Media Networks	
Amendment 2: 100 Gb/s Wireless Switched Point-to-Point Physical Layer	
IEEE Computer Society	
Sponsored by the LAN/MAN Standards Committee	
IEEE 3 Park Avenue New York, NY 10016-5997 USA	IEEE Std 802.15.3d™-2017 (Amendment to IEEE Std 802.15.3™-2016 as amended by IEEE Std 802.15.3a™-2017)



Photonics-based LO

In Thor, a photonic-based LO is used to pump up-converters:

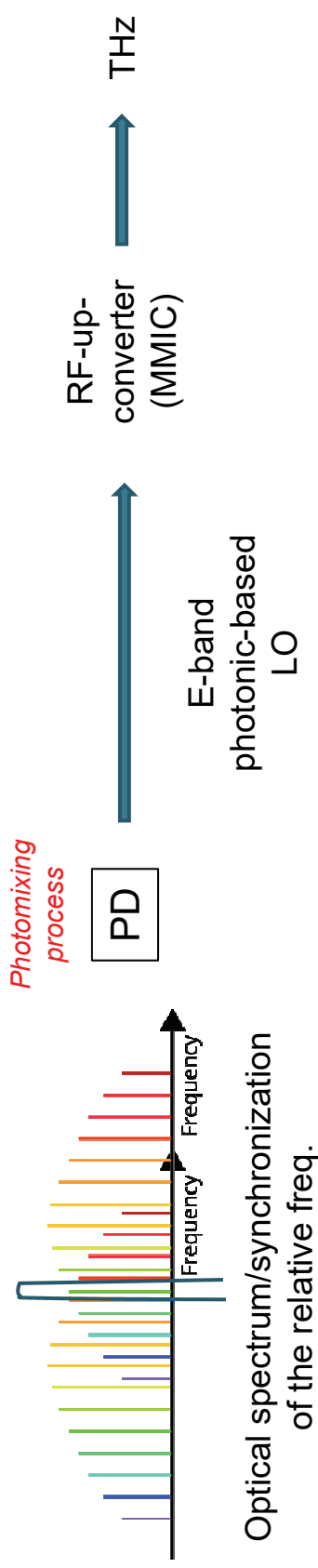
Using a fast photodiode

Dual optical feed (dual frequency optical signal) / active locking between two optical lines
(based on the correction of the optical drift).

Transformation of the optical line into a RF signal: photomixing process

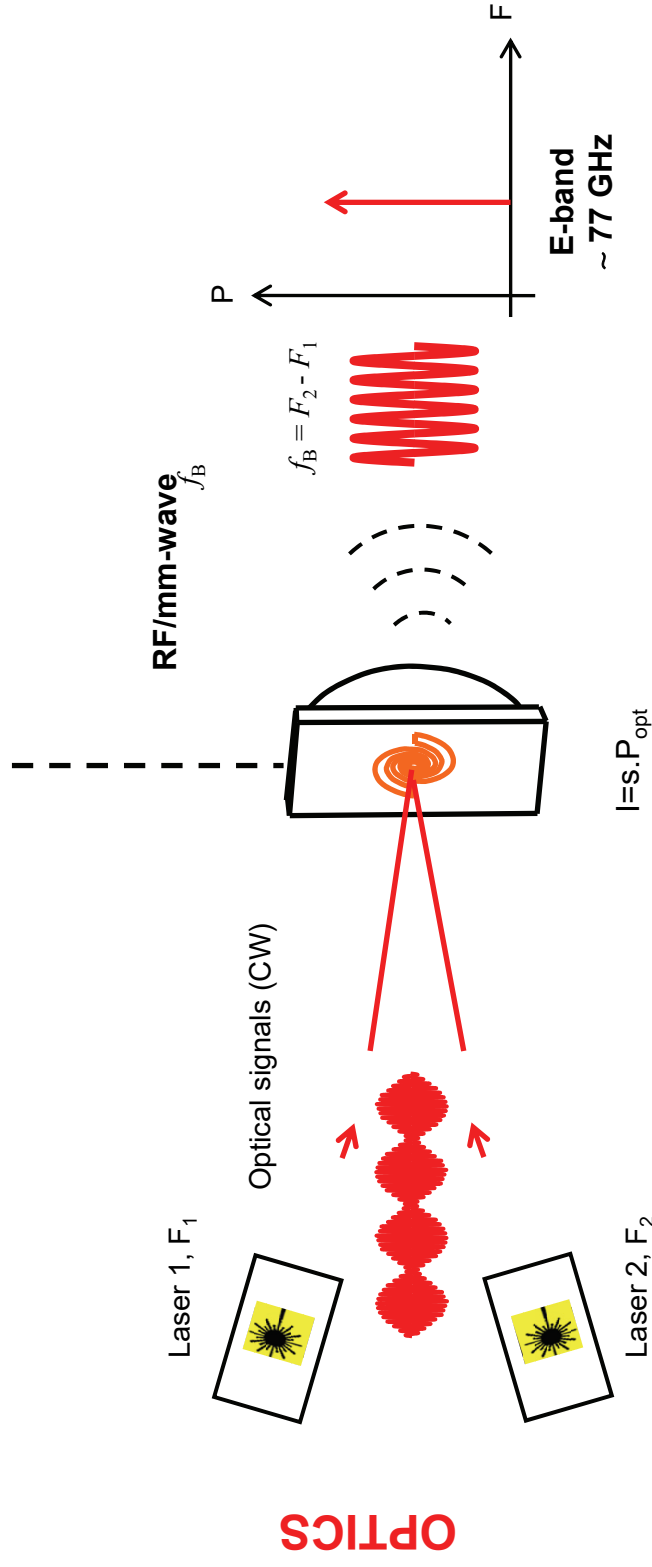
Scalability of the concept

Spectral purity

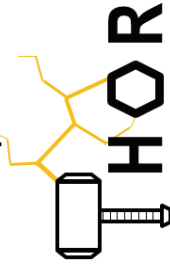


Photomixing process

Photomixing process: two optical tones are mixed down to RF/mm-wave.

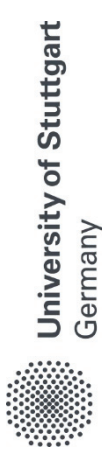
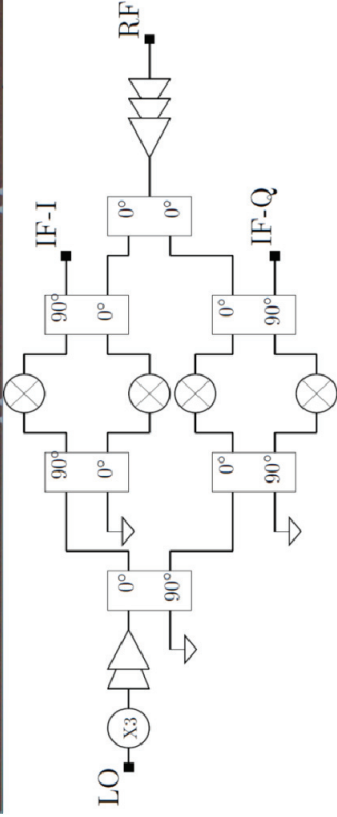
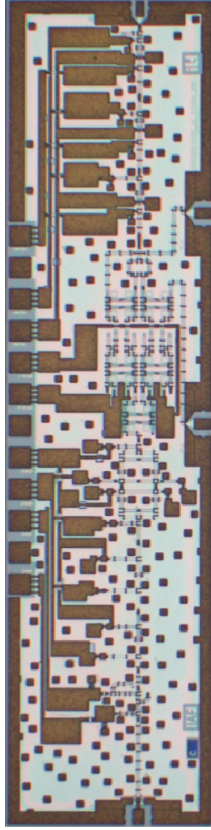


RF phase noise locked to relative optical frequency difference between laser lines.

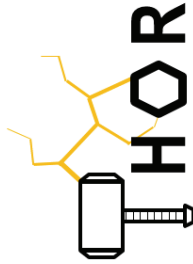
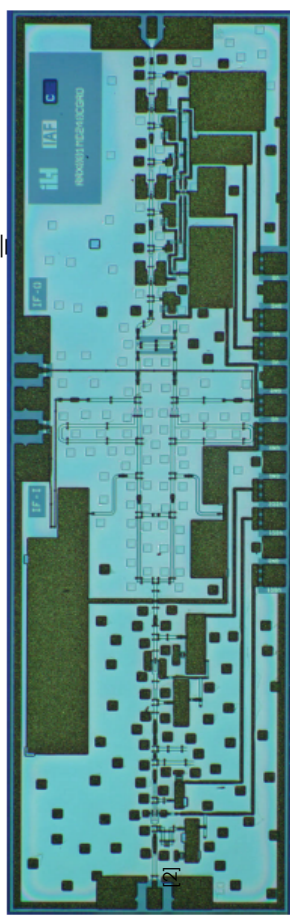
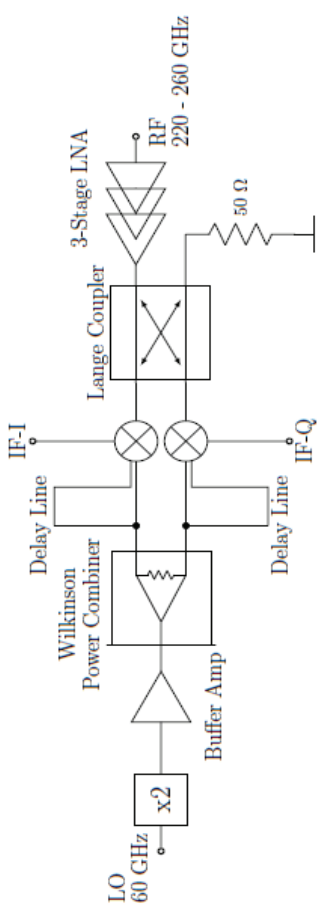


THz transceiver design

- 300 GHz RX MMIC
- Integrating [1]
 - x3 multiplier
 - Resistive mixer
 - Low noise amplifier



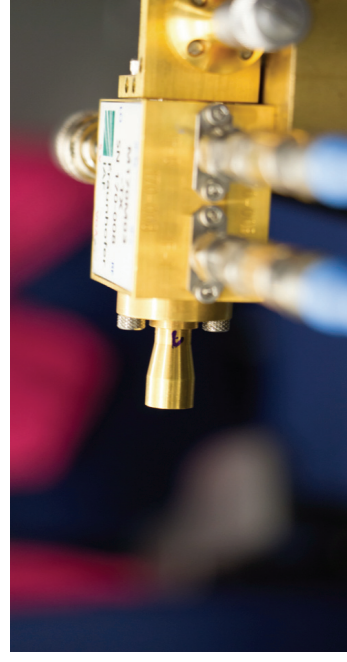
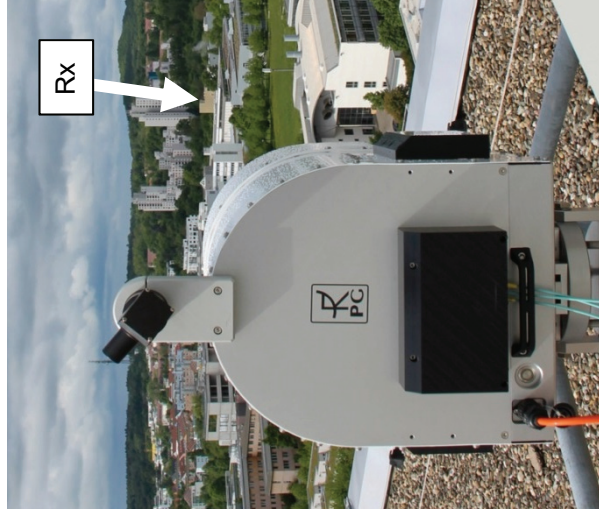
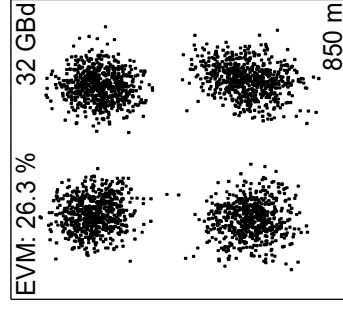
- 240 GHz RX MMIC
- Integrating [2]
 - x2 multiplier
 - Resistive sub-harmonic mixer
 - Low noise amplifier



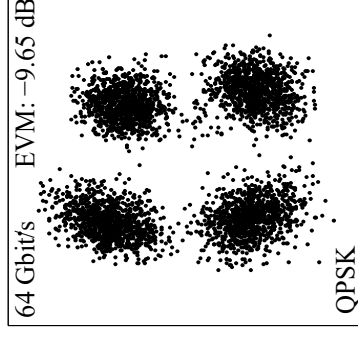
[1] I. . Dan, B. Schoch, G. Eren, S. Wagner, A. Leuther and I. Kalfass, "A 300 GHz MMIC-based quadrature receiver for wireless terahertz communications," 2017 42nd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), Cancun, 2017, pp. 1-2.
 [2] C. Grötsch, A. Tessmann, A. Leuther and I. Kalfass, "Ultra-wideband quadrature receiver-MMIC for 240 GHz high data rate communication," 2017 42nd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), Cancun, 2017, pp. 1-2.

THz link experiments

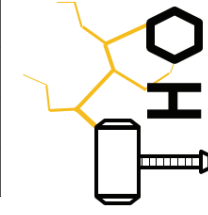
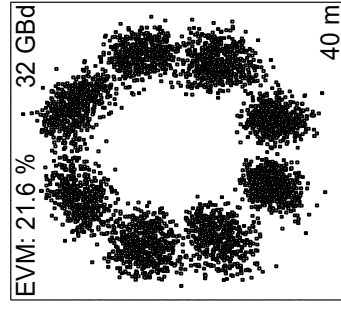
240 GHz
850 m; 64 Gbps [3]



300 GHz
1 m; 64 Gbps [5]



240 GHz
40 m; 96 Gbps [4]

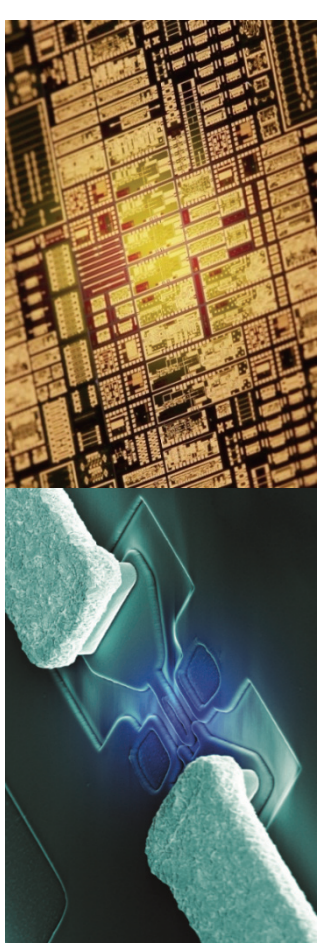


- [3] Kallfass et al., "64 GBit/s Transmission over 850 m Fixed Wireless Link at 240 GHz Carrier Frequency," 2015 *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 36, pp. 221-233.
- [4] F. Boes et al., "Ultra-broadband MMIC-based wireless link at 240 GHz enabled by 64GS/s DAC," 2014 *39th International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz)*, Tucson, AZ, 2014, pp. 1-2.
- [5] I. Dan, S. Rey, T. Mörkle, T. Kürner and I. Kallfass, "Impact of modulation type and baud rate on a 300GHz fixed wireless link," 2017 *IEEE Radio and Wireless Symposium (RWS)*, Phoenix, AZ, 2017, pp. 86-89.

Integrated THz circuits

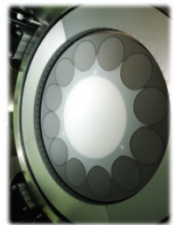


- 35 nm metamorphic high electron mobility transistor (mHEMT) offers high speed technology with leading-edge noise figures
 - High cut-off frequencies (f_T) are required for the realization of broadband front-end MMICs at 300 GHz
 - Low noise, high dynamic range receivers are needed to increase the range of 300 GHz wireless data links
- Design and fabrication of ThoR solid state THz front-end MMICs and modules
 - The front-end MMICs are processed and packaged starting with epitaxial growth of the high speed transistors



R_{ON}	250 $\Omega \cdot \mu m$
$I_{d,max}$	1300 mA/mm
V_{th}	-0.3 V
BV_{on}	> 2.5 V
$g_{m,max}$	2500 mS/mm
f_T	515 GHz
f_{max}	> 1000 GHz

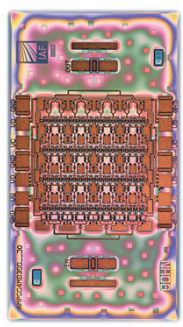
Epitaxial Growth



Wafer Processing



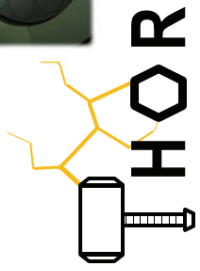
MMIC Design



On-Wafer Characterization

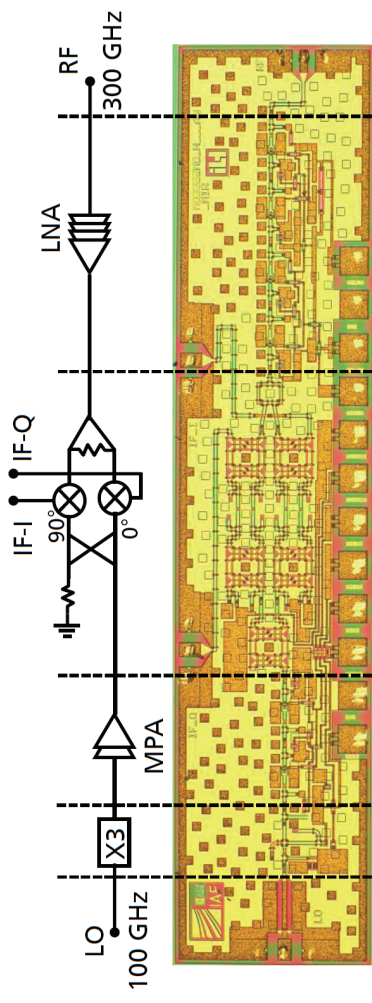


Packaging



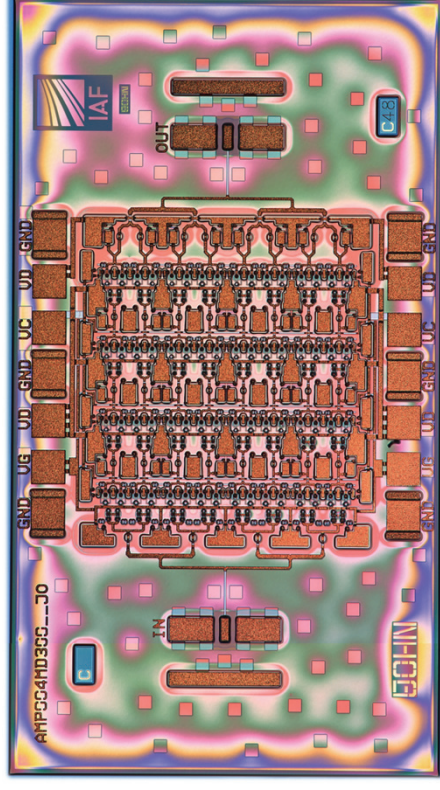
Solid-state THz front ends

- Wideband 300 GHz front ends with high dynamic range
- Designed by the University of Stuttgart
- Manufactured on Fraunhofer IAF's 35 nm mHEMT technology



Multi-functional 300 GHz RX front end (from TERAPAN project)

- Broadband solid-state high power amplifiers are under development at IAF
- Output power levels >10 mW are required to drive the TWTA in the output stage of the 300 GHz transmitter chain



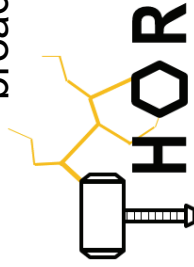
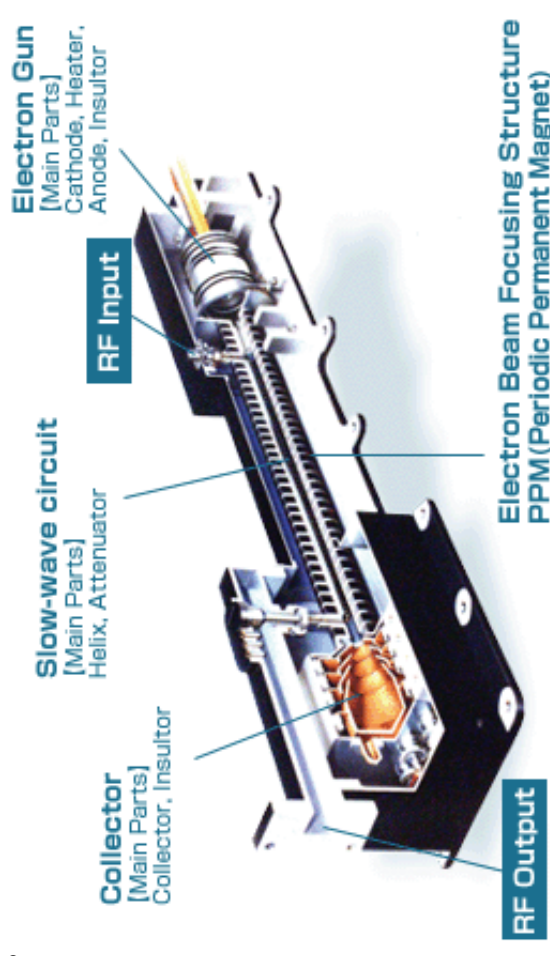
300 GHz power amplifier MMIC



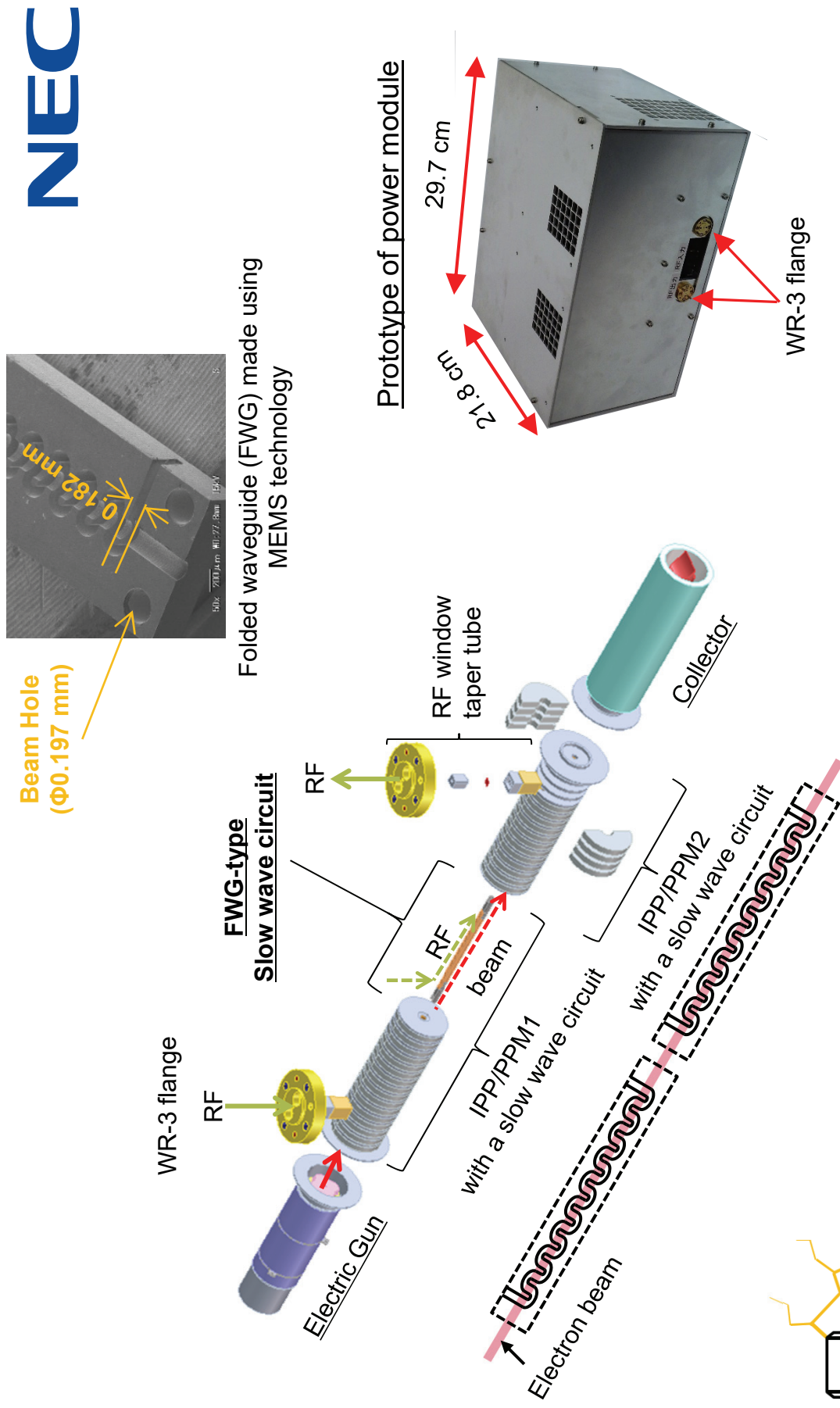
Traveling Wave Tube Amplifiers (TWTAs)

- A TWT is an electronic device used to amplify RF signals
- The TWT converts the energy of electrons in a beam into microwave energy
 - This process amplifies the low power input radio signal into a high power RF signal
- The TWT amplifier circuit can be formed using a helical coil, ring bar, folded waveguide (FWG) or coupled cavity
- TWTs are integrated with a regulated power supply and protection circuits to make high power amplifiers
 - Commonly are used as amplifiers in satellite communication and broadcasting

NEC



Exploded view of planned Thor 300 GHz band TWT

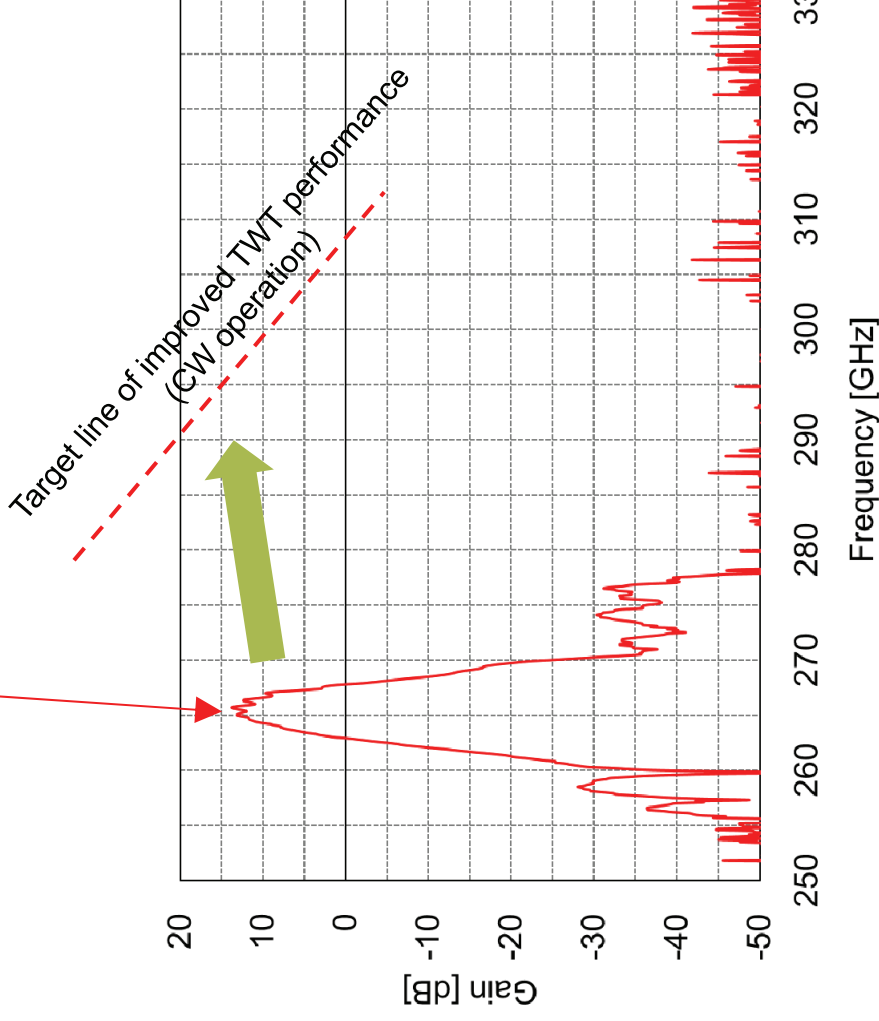


NEC



TWTA advance beyond state-of-the-art

Gain +15 dB (@265 GHz)
3 dB bandwidth 5 GHz



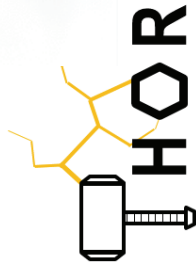
NEC

- The TWTA is a key device to achieve the power necessary for 1 km transmission in the 300 GHz band
- It is extremely challenging for a TWTA to realize enough gain and bandwidth in the 300 GHz band
- The figure shows an example of current state-of-the-art TWTA performance
- In ThoR NEC will try to realize an even higher performance TWTA for operation at 300 GHz



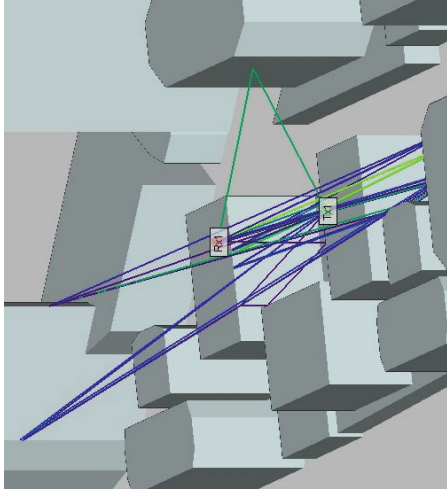
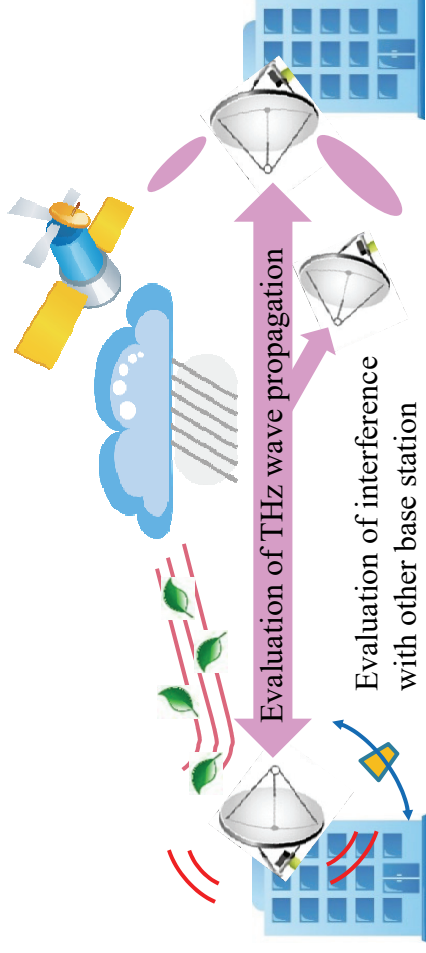
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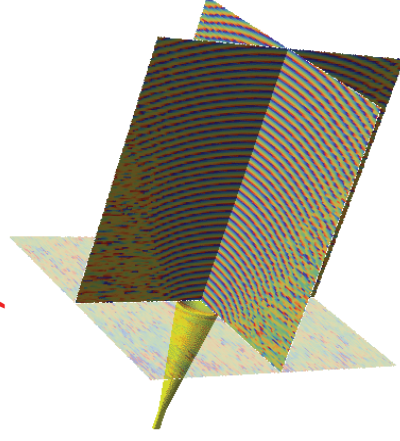
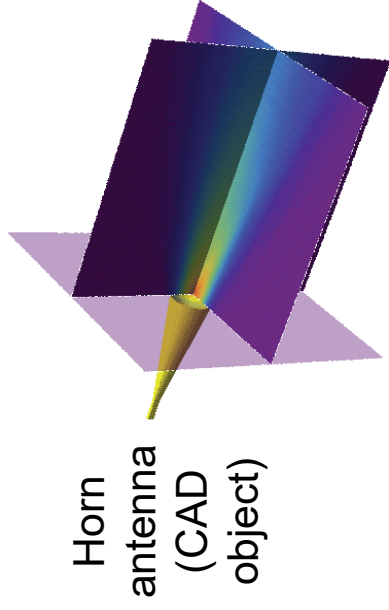
THz antennas, propagation and interference studies

- Evaluation of THz antennas and propagation
 - Measurement of THz antenna patterns
 - Propagation experiments with 300 GHz wireless links
- Deriving planning guidelines for 300 GHz BH/FH links
- Sharing investigations with passive services, development of interference mitigation techniques
 - Simulation of THz propagation for sharing study



THz near-field simulation and measurement

Simulated (at 310 GHz)

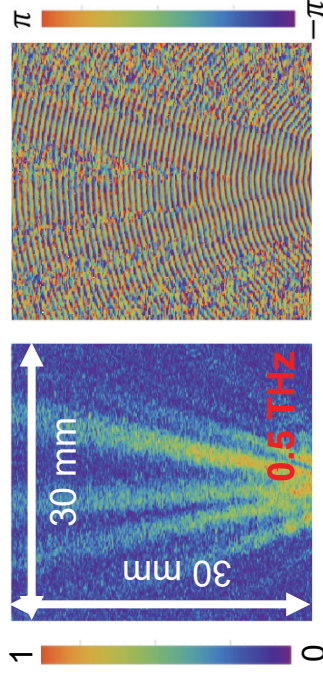
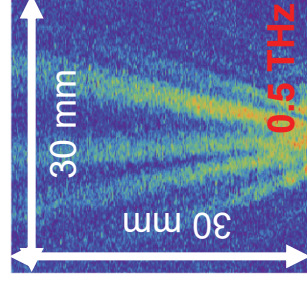
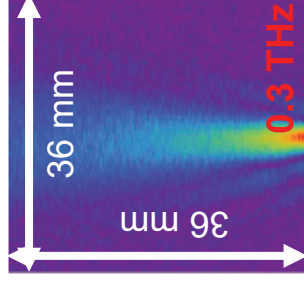
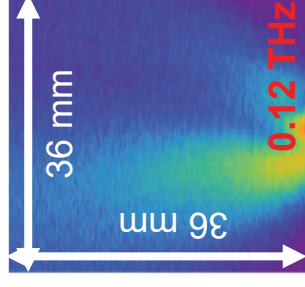


Amplitude

Phase

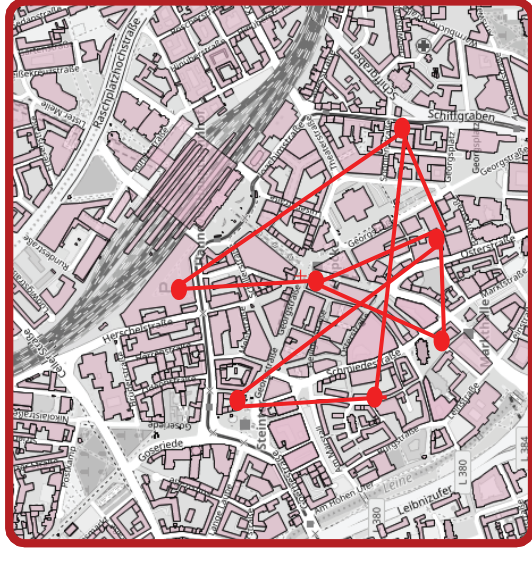
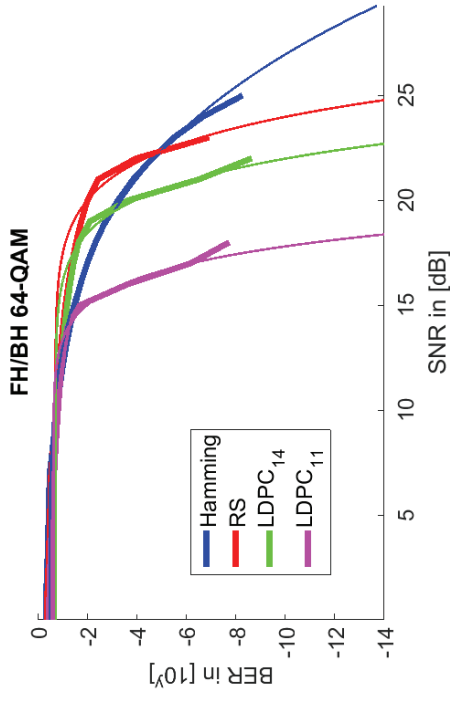
- Near-field distribution can be measured
 - Photonics-based technique
 - Wide bandwidth
 - Amplitude and phase
 - Suitable for microwave to THz frequencies
- Far-field pattern can be calculated from amplitude and phase distribution in the near-field regime
- ThoR will use the technique for antenna evaluation

Measured



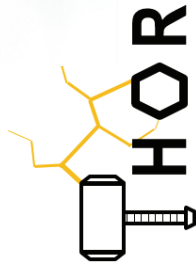
Simulation based demonstration

- Simulation based demonstration will be done using link level simulation based on
 - IEEE Std. 802.15.3d PHY layer simulator
 - Hardware impairments based on measurements from the components used in Thor
- Overall system performance and planning rules will be derived using a realistic deployment scenario in a big city



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Summary and expected output

- ThoR will apply **European and Japanese state-of-the-art photonic and electronic technologies** to build an ultra-high bandwidth, high dynamic range transceiver operating at **300 GHz** combined with **state-of-the-art digital signal processing units in two world-first demonstrations**:
 - >100 Gbps P2P link over 1 km at 300 GHz using pseudo data in indoor and outdoor controlled environments
 - **>40 Gbps P2P link over 1 km at 300 GHz** using emulated real data in a **live operational** communication network
- **The scalability of the ThoR solution to 200+ Gbps will be shown by software simulation**, which will also integrate the measured characteristics of the hardware developed and used in ThoR.
- ThoR will **directly influence and shape the frequency regulation activities beyond 275 GHz through agenda item 1.15 of WRC 2019** and will work on interference mitigation techniques and planning rules to enable deployment of 300 GHz P2P links, which comply with the outcome of WRC 2019.



Thank you for your attention!

ご清聴ありがとうございました



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Technische
Universität
Braunschweig



千葉工業大学
CHIBA INSTITUTE OF TECHNOLOGY



University of Stuttgart
Germany



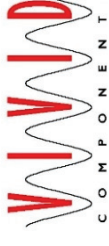
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de Lille



Fraunhofer
IAF



GIFU UNIVERSITY



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ThorProject.eu