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

ThoR project newsletter #6
May 2022

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Welcome to the final ThoR project newsletter!

In this last project newsletter we report on several areas of project activity. More details will be presented at the final workshop and demo (see below)!

- Flexible waveguide for millimetre and THz systems
- Deutsche Telekom comments on future implementations of ThoR
- Development of E-band modems in ThoR by Siklu
- Travelling wave tube amplifier advances at NEC and Waseda
- Near-field measurement for antenna testing at Gifu University
- Superheterodyne H-band frontend from University of Stuttgart
- 300 GHz mHEMT high power amplifiers from Fraunhofer IAF
- System-level testing of the ThoR Front-ends by University of Lille
- Update on the ThoR final workshop and demonstration-see back page!!!

More information is available on the project website www.thorproject.eu

Flexible waveguide for millimetre and THz systems

Broadband signal evaluation plays an important role in the ThoR project, which aims to demonstrate 300 GHz high speed radio transmission. Coaxial cables and metallic waveguides are commonly used to configure millimetre or THz systems. Although coaxial cables offer a flexible connection, the insertion loss is much larger than in metallic

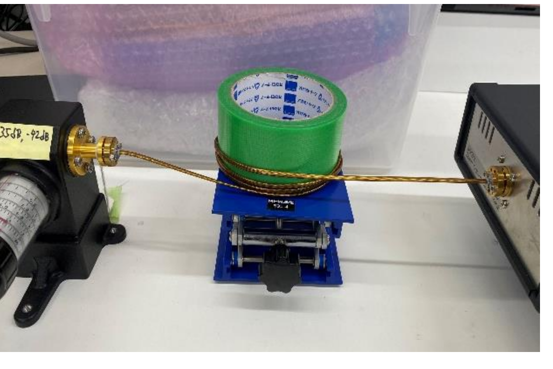

Fig. 1: Photos of the flexible waveguides made from braided metallic wire which were tested at Waseda University. (These samples were developed by Olympus).

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waveguides. Thus, such waveguides are commonly used for high performance radio systems. However, the mechanical layout design can be complicated due to waveguide configurations. This is a serious issue, especially for prototyping and experimental systems. To balance performance and deployability, researchers at Waseda University use flexible waveguides (FWGs), made from braided metallic wire. The insertion loss is less than in cables and these FWGs offer high deployability and low loss. Slight fluctuation in frequency response is exhibited due to bending, but this can be effectively suppressed using digital equalisation techniques (Fig. 2).

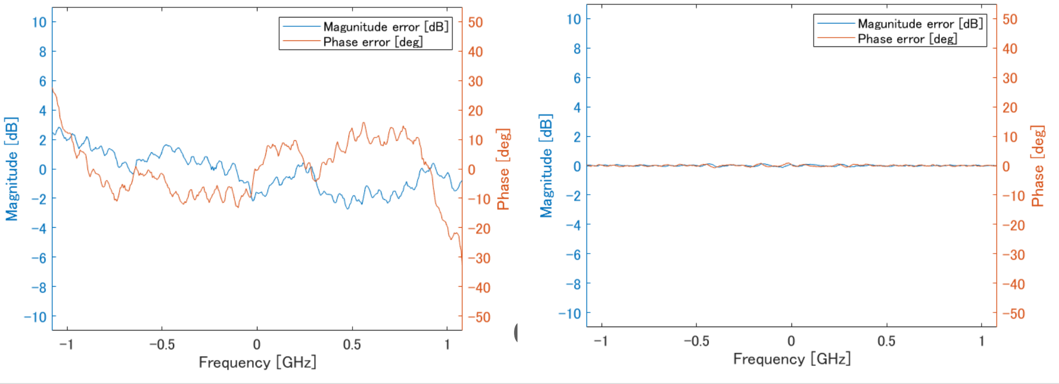

Fig. 2: Frequency response of broadband signal evaluation set-up: (left) without equalisation, and (right) with equalisation, where centre frequency is 62.64 GHz.

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Practical future implementation of ThoR technology

As a leading technology innovative telecommunication company, Deutsche Telekom (DTAG) is continuously searching for and evaluating the solutions and technologies addressing the growing need for ultra-high speed, ultra-reliable and low-latency communications. Transport networks, namely backhaul/fronthaul, represent a critical link in the network chain. ThoR targets wireless transport networks (assuming fixed services) exploiting the terahertz frequency spectrum (252-325 GHz is a key possible candidate band), which is expected to play a significant and necessary role in the next generation(s) of communication systems, 5G and beyond 5G.

To fulfil these requirements on beyond 1 Gbps user experience and transport networks, DTAG will exploit the outcomes of the ThoR project for a wireless alternative to optical fibre deployments in data-hungry use cases such as fronthaul/backhaul in C-RAN based network architecture or last mile connectivity within residential/enterprise FTTH/B. The technology validation of the terahertz solution discussed, researched and developed within the project will allow DTAG to meet the 5G and beyond targets and enhance customer QoE by providing high-quality services, increase customer satisfaction, augment group revenues and maintain customer loyalty.

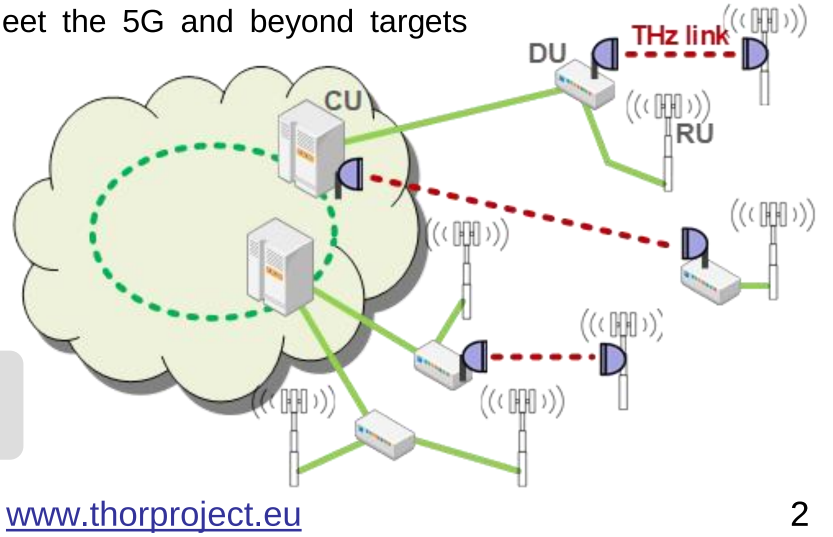

Fig. 3: Schematic of a future network including THz links.

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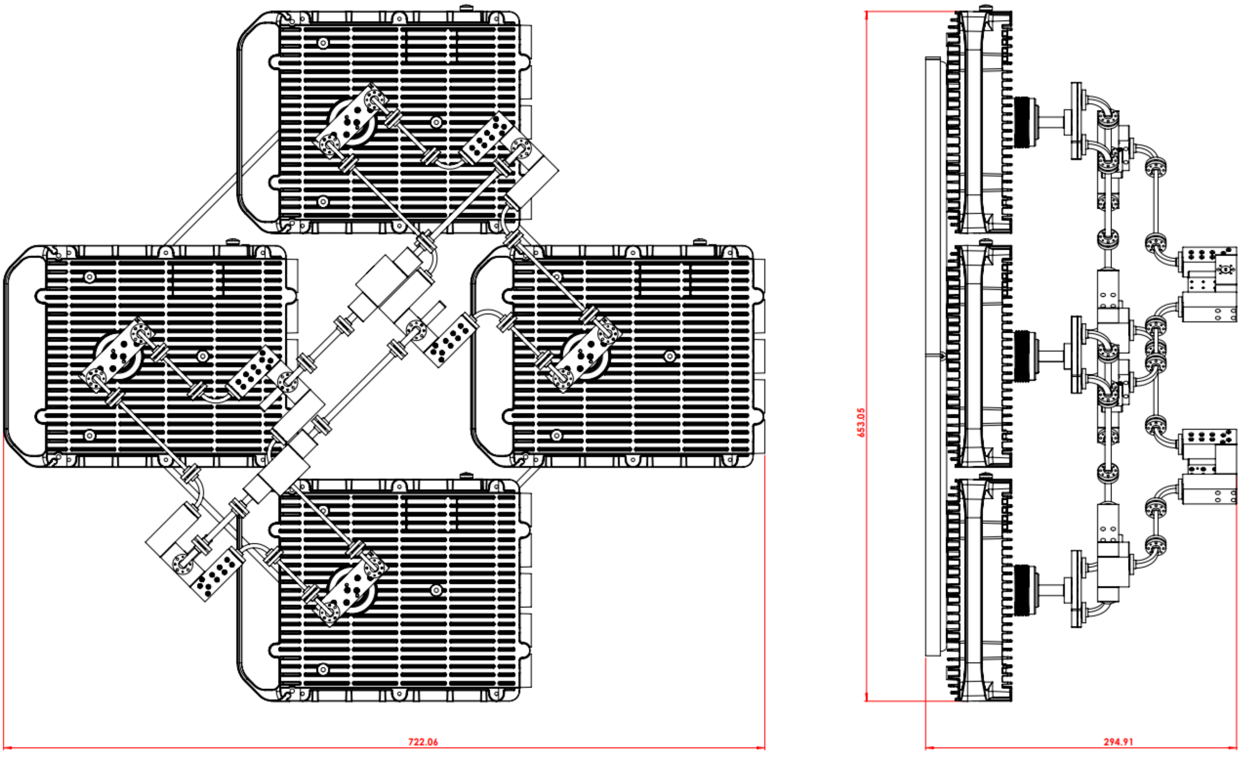
E-band modems in ThoR

The terahertz communication link implemented in the ThoR project re-uses modem technology originally targeted at mmWave bands such as E-band. In ThoR, several such modem signals are multiplexed in the frequency domain and up/down converted as a block to terahertz frequencies. The final system targeted in the demonstration is based on four parallel modems.



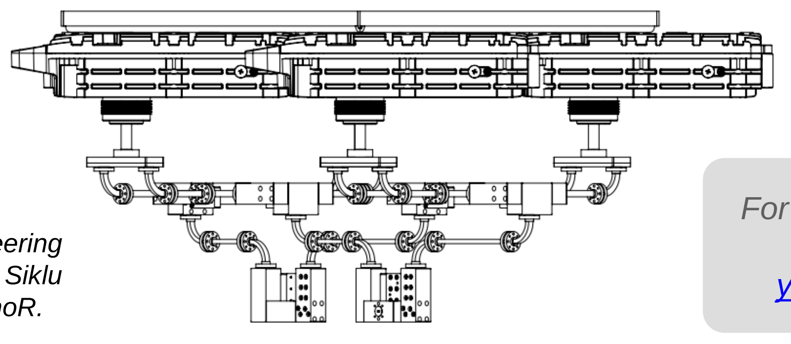


Fig. 4: Engineering drawing of the Siklu modems used in ThoR.

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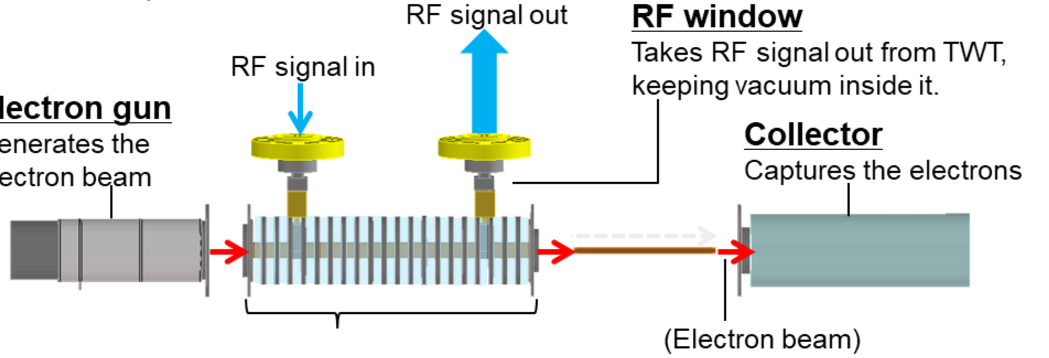
Conclusions and lessons learned by Siklu in the ThoR project:

- The individual E-band modems were capable of operating in the 300 GHz terahertz band, thanks to the good linearity and low phase noise demonstrated by the up/down conversion circuitry.
- Modem control loops such as automatic gain control (AGC), frequency tracking and TX power tracking, all operated without issue while using the up/down conversion circuitry.
- Some small degradations to SNR still exist, preventing the modems from reaching the highest modulation they are capable of. Locating and improving these degradations is an ongoing task for the remainder of the project.

TWTA advances in ThoR

A traveling wave tube (TWT) is an electronic device used to amplify RF signals (see https://www.necnets.co.jp/en/products/twt/index.html). The TWT converts the energy of an electron beam into microwave energy and amplifies an input low power radio signal into a powerful RF signal. TWTs are integrated with a regulated power supply and protection circuits to make a TWT amplifier (TWTA), which are commonly used in satellite and terrestrial communication systems.

Fig. 5: Schematic showing the operation of a TWT.



The body of the TWT is the integrated pole piece (IPP), which consists of permanent magnets and pole pieces arranged periodically for focusing the electron beam to a small cross section. A folded waveguide slow wave circuit structure (FWG-SWS) is built into the IPP. This structure amplifies the RF signal by the interaction of the electromagnetic wave (modulated wave by RF signal) with the electron beam.

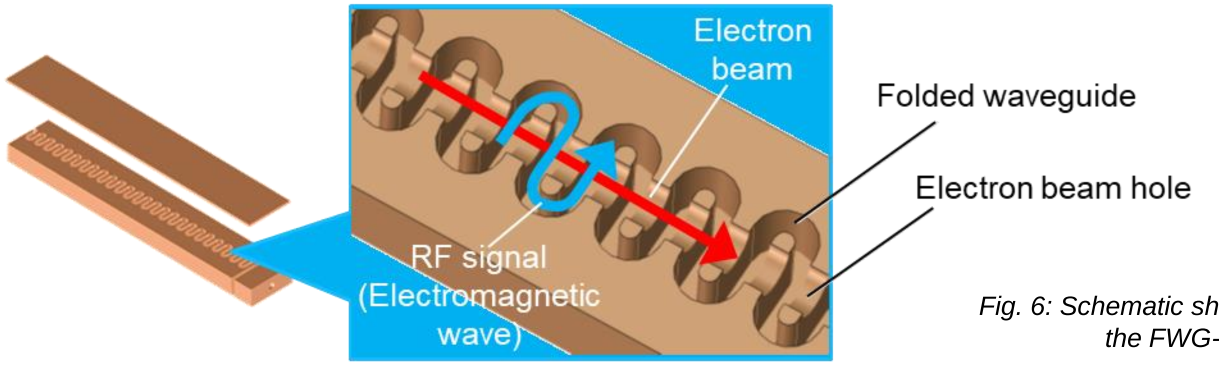


Fig. 6: Schematic showing the FWG-SWS.

Optimisation of the electron beam trajectory

In ThoR, new architectures and technologies have been introduced to achieve a 300 GHz TWT. The fourth iteration of the ThoR TWT device prototype has now been operated stably for >6 months. One of the challenges of any TWT is to ensure that the electron beam

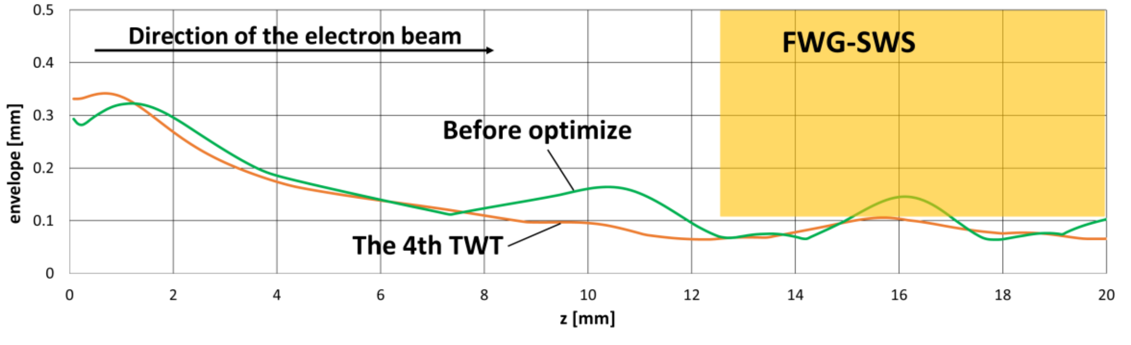


Fig. 7: Showing the electron trajectory envelope before and after optimisation.

passes through a very small beam hole with very high stability, and this is particularly difficult in the ThoR THz-band TWT. The electron beam is greatly expanded due to the influence of the thermal velocity, and it is difficult to design the electron beam trajectory. This was achieved by high resolution design of the electron beam orbit using 3D simulation. In addition, a new FWG-SWS was manufactured and a modified RF-window reduced RF loss. The fifth iteration is scheduled to be manufactured and evaluated in Q3 2022.

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Near-field measurement for antenna testing in ThoR

GIFU UNIVERSITY

The era of 6G and beyond will require many terahertz antennas to be installed in society, which will need convenient and inexpensive antenna evaluation systems. In ThoR, Gifu University developed a near-field measurement technique for 300 GHz band antenna testing [1]. The developed technique is based on photonics, not a vector network analyser (VNA). The test (RF) and reference (local oscillator) signals for the measurement are generated by beating two independent free-running lasers. The optical beat is converted to an RF signal using uni-travelling carrier photodiodes (UTC-PDs). Although the frequency and phase of the RF signal fluctuates, the system can map not only amplitude but also the phase distribution thanks to the self-heterodyne technique. Figure 8 shows a photo of the near-field measurement set-up around an antenna under test (AUT).

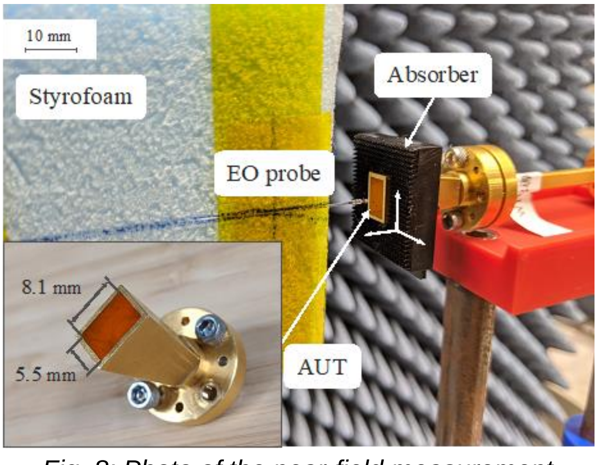
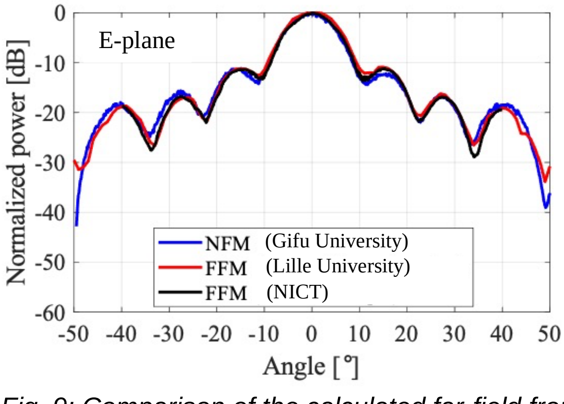


Fig. 8: Photo of the near-field measurement set-up around an AUT.

The amplitude and phase distribution on the antenna surface is measured by scanning an electro-optic (EO) probe developed at Gifu University. By conducting near-field to far-field conversion, the far-field pattern (radiation pattern) of the AUT can be evaluated. In ThoR, Gifu researchers compared three results: (1) the far-field pattern calculated from the near-field pattern measured by the developed system, (2)



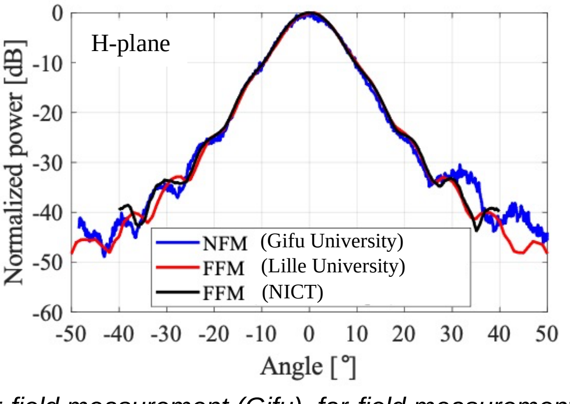


Fig. 9: Comparison of the calculated far-field from near-field measurement (Gifu), far-field measurements using a set of sources/direct-detection (Lille) and far-field measurements using the VNA technique (NICT).

*[1] 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 **3**, pp. 24-31 (2022). doi: 10.1109/OJAP.2021.3133470.*

the directly measured value based on source/direct detection technique at University of Lille and (3) the far-field pattern measured directly using a VNA at NICT. Fig. 9 presents a comparison between these three results, which show very good agreement. It is proposed that such photonics-based near-field measurement systems could pave the way for the agile characterisation of terahertz antennas for 6G and beyond.

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Design and verification of superheterodyne H-band transmit and receive frontend

University of Stuttgart Germany
Fraunhofer IAF

To provide the ultra-broadband transceiver frontend capabilities to suit the ThoR frequency plan in compliance with the IEEE802.15.3d standard, fully-integrated H-band monolithic millimetre-wave integrated circuits (MMIC) have been designed by the Institute of Robust Power Semiconductor Systems from the University of Stuttgart. Applying comprehensive circuit-level as well as electromagnetic field simulations, the frontends have been implemented in the state-of-the-art 35 nm InGaAs mHEMT technology developed by Fraunhofer IAF.

While the transmit and the receive MMIC both implement the same local oscillator (LO) path consisting of a frequency tripler and a buffer amplifier driving a resistive mixer, the transmitter also includes an RF power amplifier stage to increase the transmit power, whereas the receiver uses a low-noise amplifier stage to pre-amplify the received signals. Featuring a unique broadband IF interface covering the entire E-band from 60 to 90 GHz, as well as LO frequency tuning capabilities in the range from 70 to 77 GHz, various RF channels in the range from 280 to 315 GHz can be addressed by the ThoR frontend.

In the frame of ThoR DEMO2-1, an extensive characterisation of the Tx and Rx modules has been successfully conducted using continuous-wave as well as modulated signals. Furthermore, the real-time capabilities of the H-band hardware have been successfully demonstrated by setting up a short-range full-duplex wireless link in conjunction with a set of 70/80 GHz modems provided by Siklu.

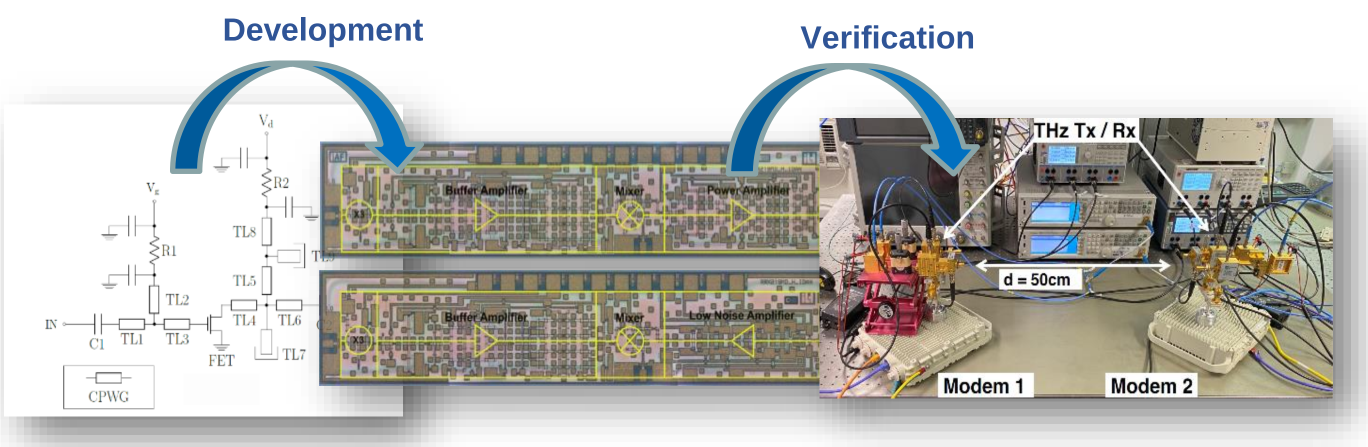

Fig. 10: Showing the progression from design, implementation and verification of the ThoR frontend.

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300 GHz mHEMT high power amplifiers

As discussed on the previous page, the ThoR frontends, which operate in the frequency range around 300 GHz, have been developed in collaboration between the University of Stuttgart and Fraunhofer IAF, using Fraunhofer's high speed InGaAs-channel HEMT technology. To achieve sufficient output power levels for the large transmission distances that are targeted with the point-to point links in the ThoR project (up to 1 km), state-of-the-art high power amplifier circuits and modules have been successfully designed and assembled at Fraunhofer IAF.

Using a novel amplifier topology based on cascode and common-source devices, more than 20 mW of output power has been demonstrated at circuit level. With more than 20 dB of gain over the frequency band from 275 to 335 GHz, which was achieved after packaging into WR-3.4 waveguide modules (Fig. 11), the power amplifier modules are well suited for wideband wireless applications at the lower THz frequency range. In addition, >10 mW of saturated output power has been measured with the packaged HEMT devices, while achieving 55 GHz; the largest power bandwidth reported in the 300 GHz band. Based on these power amplifiers that have been realised in the ThoR project, broadband and highly-linear 300 GHz amplifiers are currently being developed at Fraunhofer IAF, targeting power levels in the range of 20 to 50 mW on waveguide level.

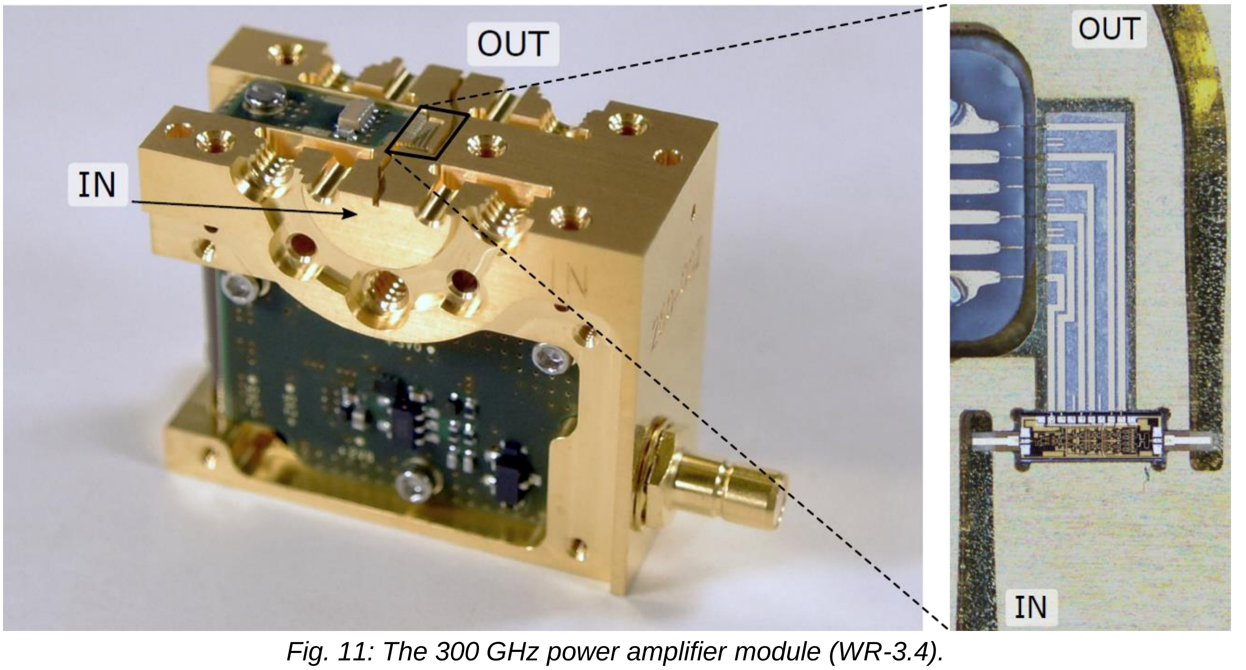

Fig. 11: The 300 GHz power amplifier module (WR-3.4).

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System-level testing of the ThoR RF frontend

The ThoR approach considers a combination of several core technologies towards the full RF front-ends. The super-heterodyne approach is enabled by solid-state up/down converters while local oscillator frequencies are based on a photonic approach (photonic LO) to reach harmonic-free pumping of the THz up/down converters. In this period, full assembly of a ThoR RF frontend, pumped by a photonic LO has been achieved. Meanwhile, targeting outdoor demos, link budget and non-linear response of the system was investigated using emulation of fast I/Q IF signalling at both RF (evaluation of amplifier non-linear impairments) and IF ports (non-linear response of the full RF chain). Figure 12 shows an example of amplifier non-linear response for 50 Gbps signal amplification using two developed medium power amplifiers (MPAs).

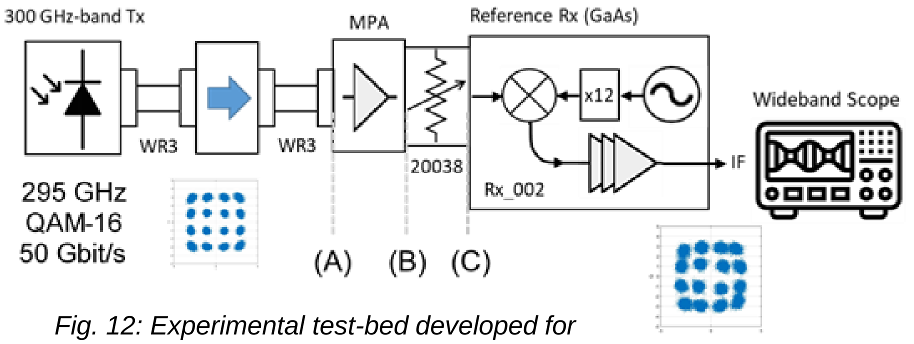

Fig. 12: Experimental test-bed developed for evaluation of the linear amplifier response under modulated signal (50 Gbps).

Experimental evaluation of the amplifier non-linear response is of utmost importance to ensure the required linearity of the full RF chain. In Figure 13, the error-vector magnitude evolution for MPA output power (B) enables determination of the effective linear region, *i.e.* here close to 0-2 dBm, where EVM impairment is limited.

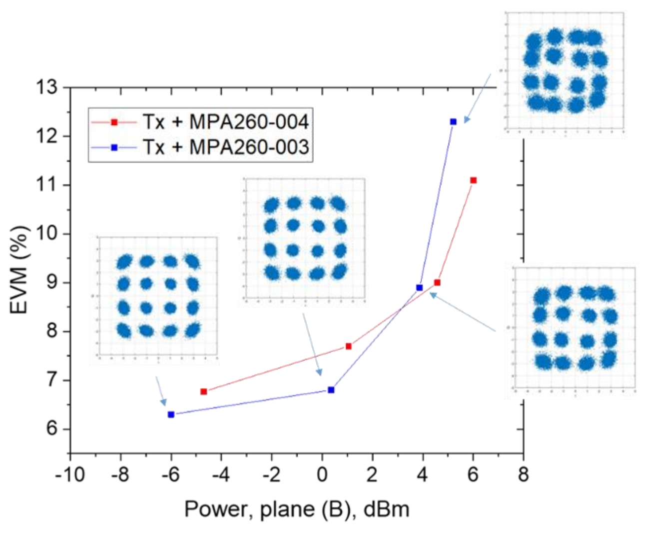

Fig. 13: Showing the error vector magnitude evolution with MPA output power.

This enables determination of the MPA maximum operation point when using it with modulated data flow in the 300 GHz range. The combination of MPA and up/down converters is currently realised to analyse i) full chain linearity and ii) link budget to finalise the configuration of the final ThoR demos (outdoor configurations using modems). In that case, the V/E band modems will use advanced modulation formats (*e.g.* QAM-128), where system non-linearity is the main critical parameter with the system gain/link-budget.

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ThoR final workshop and demo

Unfortunately the COVID-19 restrictions forced the ThoR consortium to postpone this event. However, there is some good news! The project has been extended and <u>the final workshop and demo will take place “face-to-face” at TU Braunschweig (or it is possible to join online) on 29-30 Jun-2022</u>. The event will include invited speakers, a live demo link between campus buildings as well as a social event. For the agenda and more info, please visit:

https://thorproject.eu/events/thor-final-workshop-and-demo/

<u>Places are limited!</u> *If you would like to reserve a place to attend in person or online, please send an email to: bruce@vividcomponents.co.uk*