# iBROW project newsletter #6

*Sep-2018*

**Welcome to the sixth iBROW project newsletter!**

*iBROW is a research project supported by the European Commission through Horizon 2020 under Grant Agreement 645369.*

All good things must come to an end; this will be the final iBROW newsletter! The technical work in the project has concluded and shortly the final administrative details will be complete. The project has been a major success and achieved or exceeded all its key targets. A number of world firsts and records have been achieved:

- Improved RTD devices
    - First ever RTDs from direct silicon wafer bonding (p. 3)
    - New state-of-the-art in RTD power & efficiency for e-RTDs and RTD-PDs (p. 5)
    - RTDs demonstrated from direct epitaxial growth on silicon substrate
- Direct application of RTDs in wireless communications systems
    - New state-of-the-art W- (84 GHz) and J-band (300 GHz) transmission (p. 5-6)
    - First transmission using RTD-PDs with advanced modulation formats (p. 7)
    - First ever DVB-T audio/video transmission using RTD-PDs (10 GHz) (p. 8)
- Practical implementation of RTDs for commercial systems
    - Improved dynamic measurement of laser diodes for driving RTDs (p. 4)
    - 10 Gbps RTD-LDs packaged and designs for RTD-PD packaged devices
    - Ground-breaking simulation (p. 2) and experimental channel modelling (p. 9)

Some of these breakthroughs are described in this newsletter. More info and links to scientific publications may be found on the project website.

The project culminated in a THz Electronics Workshop hosted by University of Glasgow (23-24 Apr-2018) which was attended by 85 researchers from all over the world. The interest in the project and its topics was so high that the next event is already planned for 2020, so please keep in touch!

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| Coordinator | Edward Wasige | edward.wasige@glasgow.ac.uk |
| Admin | Bruce Napier | bruce@vividcomponents.co.uk |

# RTD, RTD-PD, and RTD-LD modelling packages

Because current electronic circuit simulators, such as SPICE or ADS, cannot be used to simulate circuits incorporating double barrier quantum well (DBQW) RTD structures, iBROW developed computational models of RTD and RTD-PD devices, and associated RTD-LDs. The resulting modelling packages are suitable for system and link level simulations. The packages cover forced Liénard oscillator representations of RTD oscillator circuits (Fig. 1), including its photo-detection capabilities, and optoelectronic transmitters based on hybrid integration of RTDs and LDs (Fig. 2). These simulation packages make use of auto-fitting routines of the RTD experimental I-V characteristics (Fig. 3).

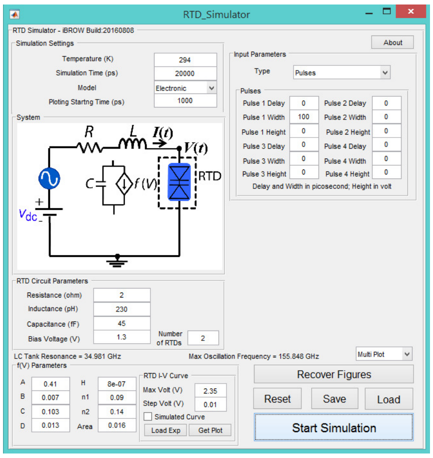



*Fig. 1: RTD oscillators*

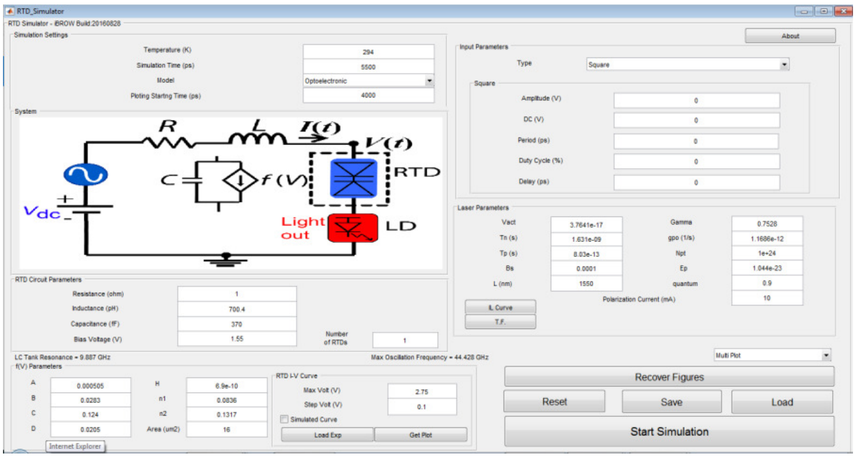



*Fig. 2: RTD-LD circuit simulation package*

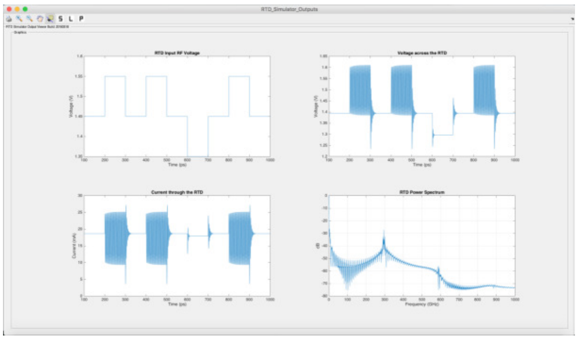


*Fig. 3: RTD package (typical output)*

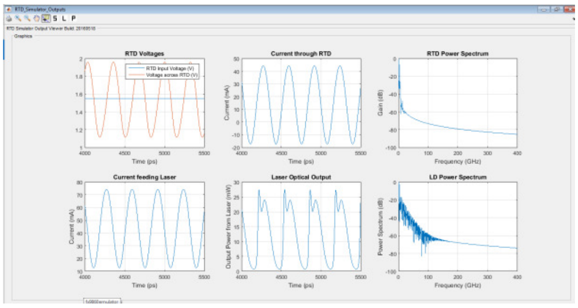


*Fig. 4: RTD-LD package standard output*

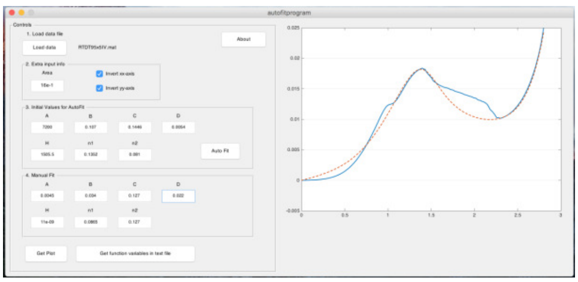


*Fig. 5: RTD I-V auto-fitting package*

Fig. 1 shows the front end of the RTD circuit simulation package; a typical output is displayed in Fig. 3. The operator can define the circuit parameters (*R*, *L*, *C*, *F*(*V*)), and the type of RF input signal: *e.g.* pulsed, square, sinusoidal, or add a new form. With this user friendly tool, it is possible to load new I-V curves or save the current setting parameters among other possibilities. Typical outputs include the RF driving signal, the voltage across and the current flowing through the RTD, and the circuit power spectrum. Fig. 2 shows the front end of the RTD-LD circuit simulation package. Its standard output is displayed in Fig. 4 and includes the current driving the LD, the optical output power and the frequency response. As shown in Fig. 5, an RTD I-V auto-fitting package capable of producing RTD I-V fittings, accurately represents the experimental I-Vs, with minimal operator intervention and can be incorporated into conventional electronic design automation software such as SPICE and ADS.

For more info contact: José Figueiredo
jmfigueiredo@fc.ul.pt

# First ever RTDs on silicon substrates

A key part of the iBROW project was to develop RTDs on silicon substrates to demonstrate a viable route to low cost manufacture in the longer term. One of the approaches to this to show proof of principle was a bonded wafer method.

iBROW has demonstrated for the first time an InGaAs/AlAs RTD directly bonded on silicon substrate, as well as complete RTD-based millimeter-wave oscillators. This achievement leverages the University of Glasgow's design expertise in RTDs and RTD-based oscillators, III-V Lab's InGaAs/AlAs epi-growth using MOVPE, CEA-LETI's III-V-on-Si wafer bonding and III-V Lab's wafer processing as well as RTD-based circuit mask design and characterization.

The fabrication process includes three main steps:

i) Firstly a high performance InGaAs/AlAs RTD structure is grown on a standard InP two inch wafer

ii) Secondly, the InP wafer is bonded onto a low cost silicon wafer

iii) Finally, the InP-on-Si wafer is processed for the complete realization of RTD devices and RTD-based oscillators, as depicted in Fig. 6.

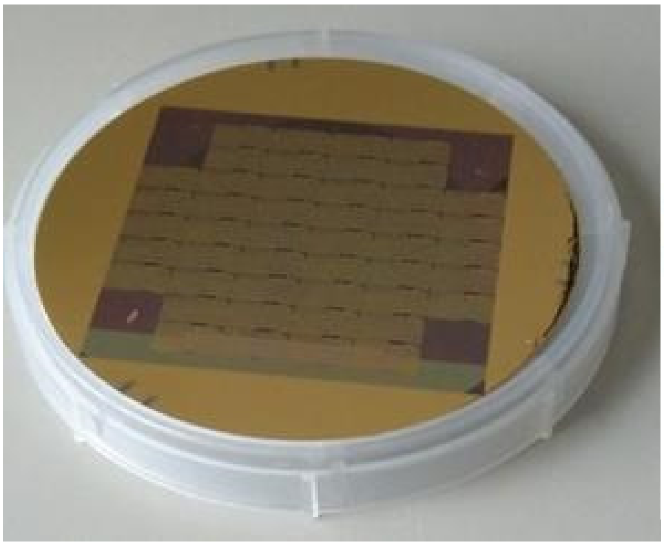


Fig. 6: iBROW's 2-inch InGaAs/AlAs-on-Si wafer to realise the first RTD oscillators on silicon substrate.

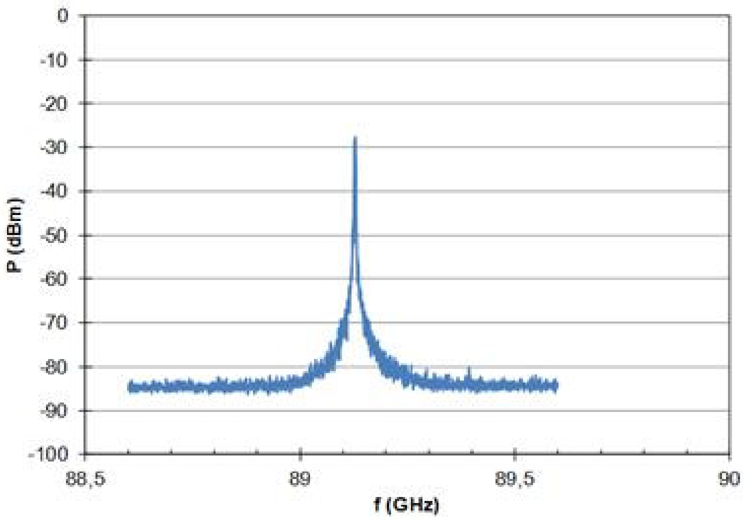



Fig. 7: Showing the performance of the iBROW 89 GHz InGaAs/AlAs-on-Si RTD-based oscillator.

After preliminary RF measurements, 89 GHz InP-on-Si RTD oscillators have been demonstrated, as presented in Fig. 7. Further measurements on various designs of RTD and oscillators are on-going at Glasgow and III-V Lab.

This new RTD-on-Si technology opens the way to low cost, energy efficient and compact mm-wave RTD-based circuits integrated with CMOS for future high capacity wireless transceivers.

For more info contact: Christophe Caillaud christophe.caillaud@3-5lab.fr

# RIN measurement platform for laser evaluation

The iBROW project considered not only RTDs themselves, but the links between the wireless network and the fibre optic core infrastructure. FP and DFB lasers from CST are key components in these links, both as the source for the RTD signal (downlink) and modulated by the RTD in the uplink. This required a detailed understanding of the dynamic performance of the lasers.

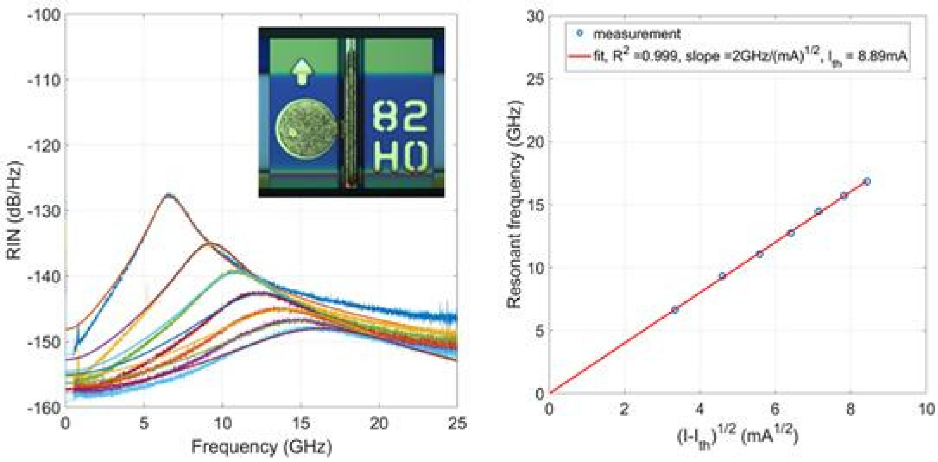



*Fig. 8: Schematic representation of the RIN measurement set-up used for high speed laser characterisation within the iBROW project.*

Based on work in iBROW, dynamic measurements of laser chips can now be performed at CST Global after successful implementation of a RIN measurement set-up. Distributed feedback laser diodes and high speed Fabry-Perot laser diodes have been evaluated with this kit. The knowledge generated has helped in optimising and re-designing current high speed laser solutions.

Directly modulated (DM) DFB lasers are investigated aiming to comply with high speed O-band and C-band communication specifications. In particular the effect of wavelength detuning and temperature over dynamics has been documented and shared in dissemination activities within the iBROW project.

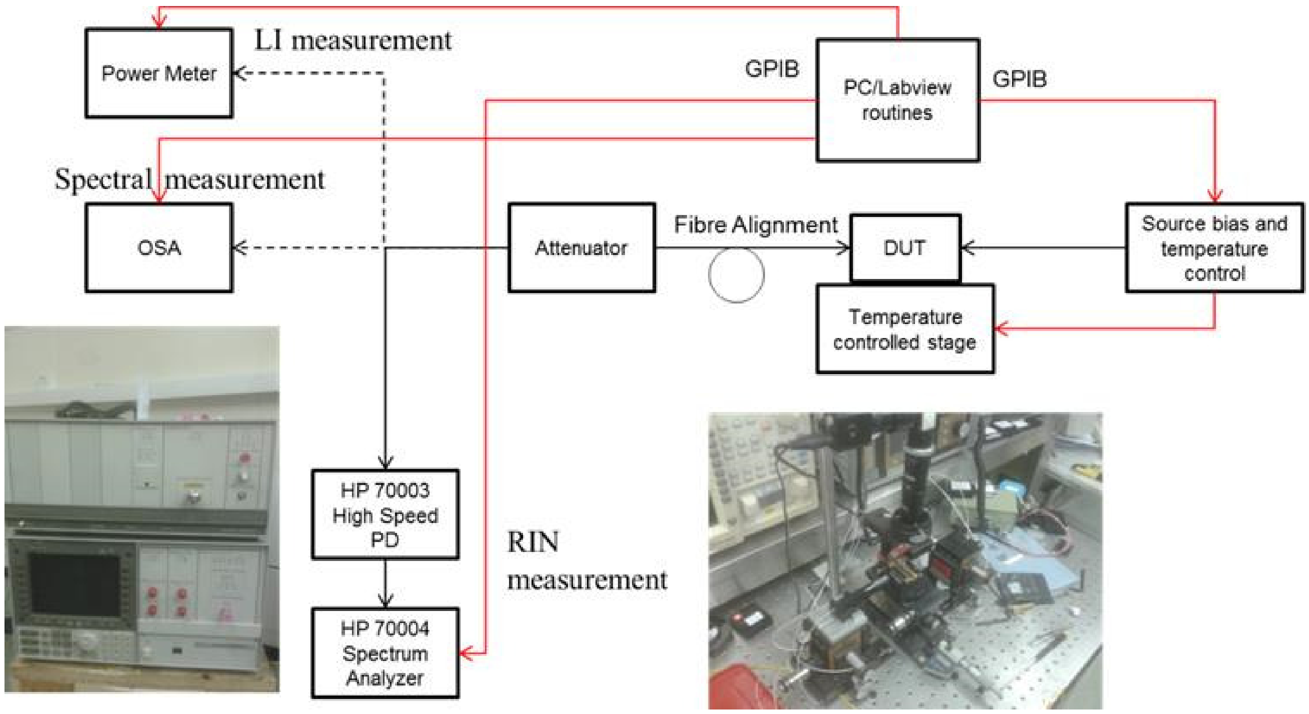



*Fig. 9: Typical RIN measurement of an FP laser as those used as optical sources within the iBROW project*

For more info contact: Horacio Cantu hcantu@compoundsemi.co.uk

# mm-wave/THz multi-gigabit wireless links and microwave/photonic interfaces

University of Glasgow

## RTD high capacity wireless link architecture

The block diagram of the wireless system and measurement set-up is illustrated in Fig. 10a and 10b. On the transmitter (Tx) side, the $2^{15}$-1 PRBS (pseudo-random binary sequence) data is superimposed over DC bias through a bias tee. The modulation scheme is ASK modulation. The output of the transmitter, the RTD voltage controlled oscillator (RTD-VCO) is connected to a horn antenna. On the receiver (Rx) side, an identical horn antenna is used to receive the modulated signal. Then it is demodulated by a Schottky barrier diode (SBD) envelope detector and amplified by a low noise amplifier (LNA) before it is received by the oscilloscope.

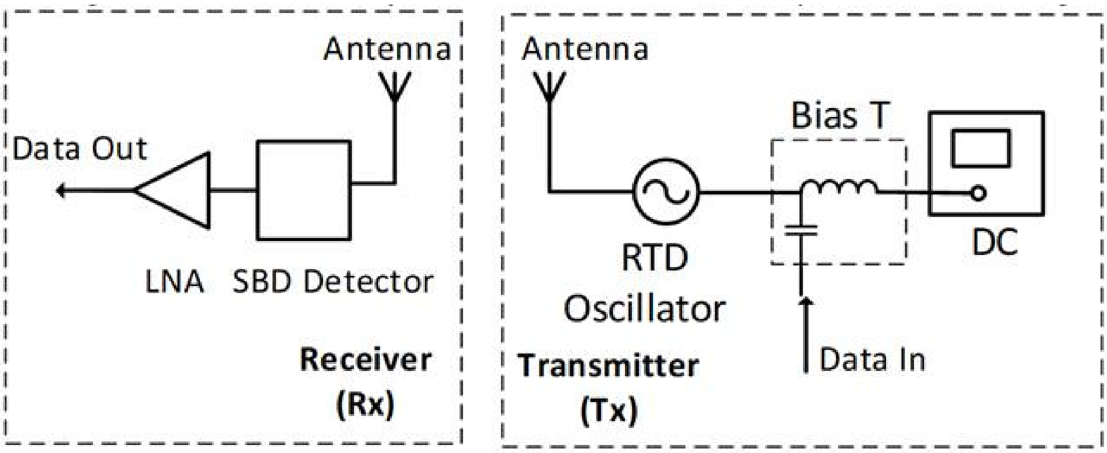



*Fig. 10a: Block diagram of the wireless system architecture. Both the Tx and Rx modules use identical horn antennas to send the modulated RTD signal across free space.*

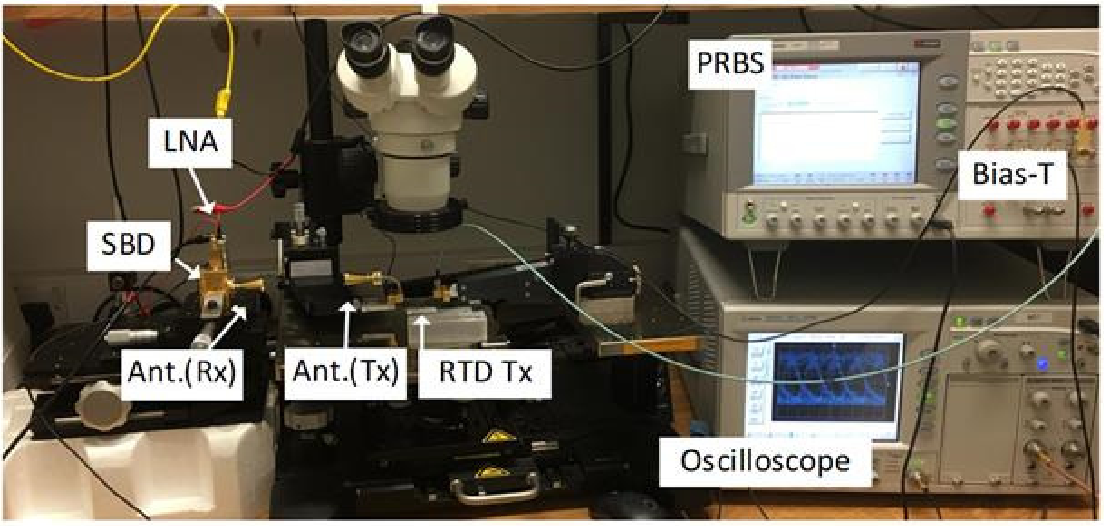



*Fig. 10b: Photograph of the actual equipment used in the measurement set-up in the laboratory at the University of Glasgow which implements the schematic in Fig. 10a.*

## Record W-band high power RTD transmitter

The high power RTD oscillator was characterized on-wafer and the central frequency was identified as around 84.5 GHz, with a tunable range of about 150 MHz. The measured maximum power is about 2 mW. This is the highest power reported for a W-band RTD oscillator. The best measurement results of 10 Gbps and 15 Gbps eye diagrams are shown in Fig 11. The link distance between the transmitter and the receiver is 50 cm.

For more info contact: Abdullah Al-Khalidi Abdullah.Al-Khalidi@glasgow.ac.uk

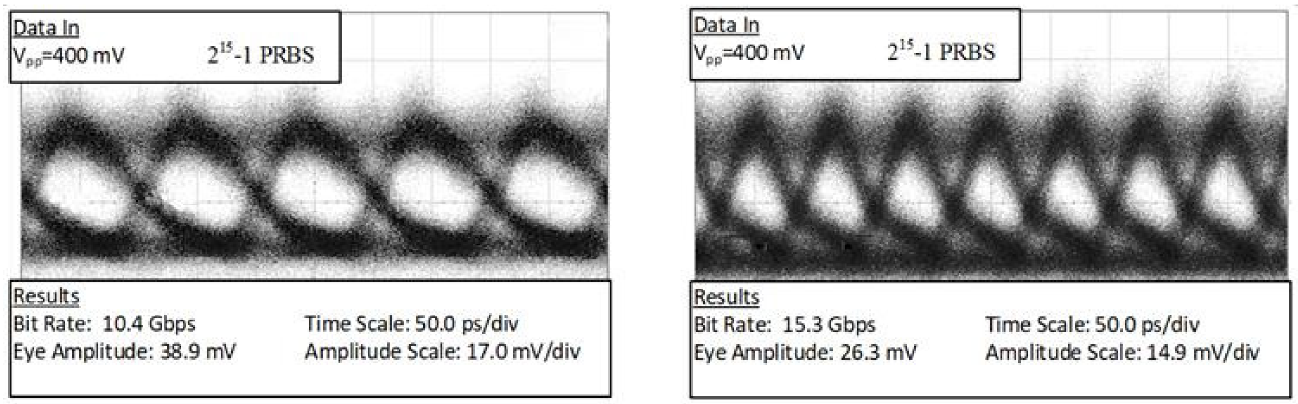
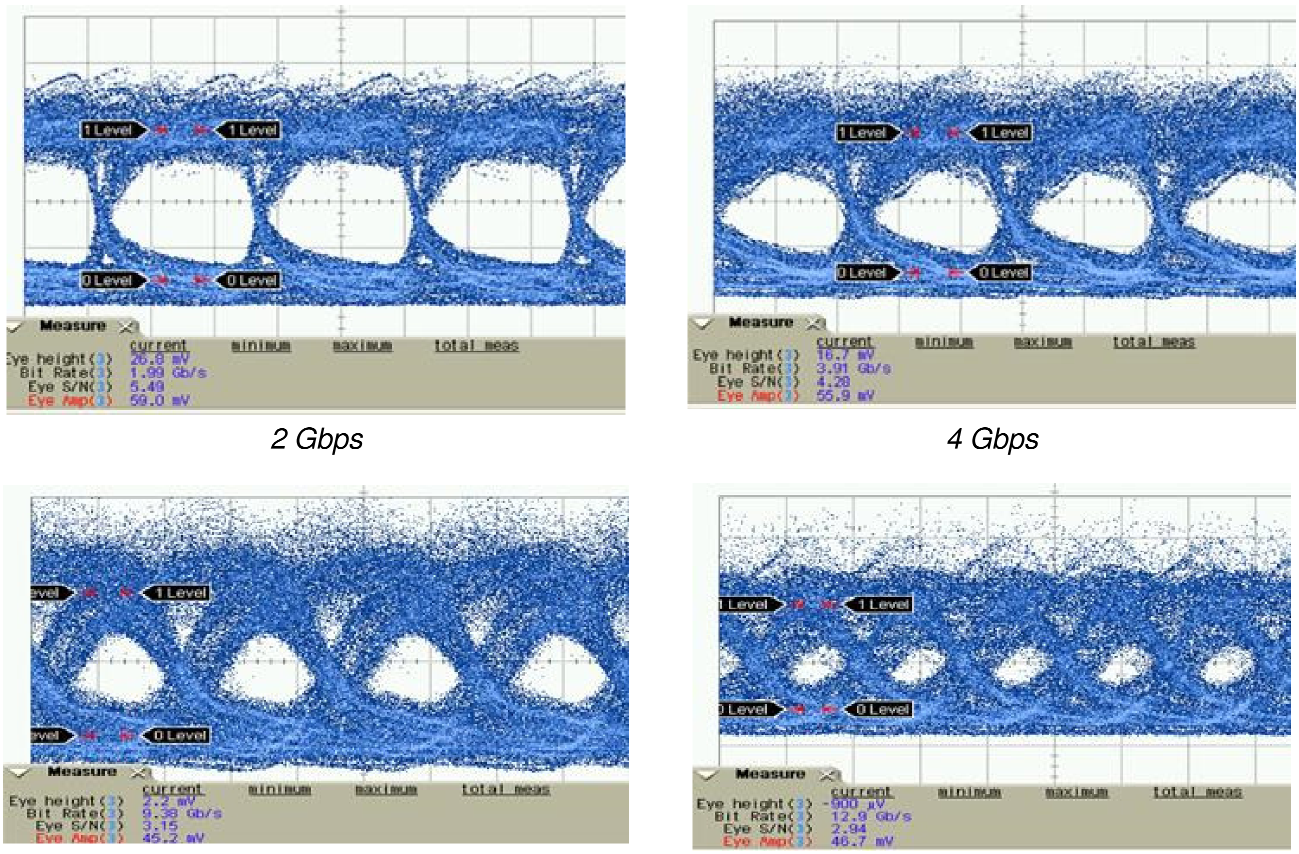



*Fig. 11: 10 Gbps and 15 Gbps wireless data transmitted over a 84 GHz carrier signal.*

## Record J-band high power RTD transmitter

J band high power RTD oscillators have also been developed in this project. The highest measured oscillation frequency was 260 GHz and output power was 1 mW, which is also the highest power reported for J-band RTD sources. By using a similar wireless measurement set-up, the measured eye diagram is shown in Fig. 12. In an optimised measurement set-up with lenses to focus the THz radiation, up to 6 Gbps error-free and 25 Gbps with correctable BER with ranges of up to 20 m was demonstrated.




*2 Gbps* *4 Gbps*

*9 Gbps* *13Gbps*

*Fig. 12: Eye diagrams of up to c.13 Gbps wireless data transmitted over a 260 GHz carrier signal.*

These results demonstrate low cost and simple wireless transceiver architectures that can achieve at least 10 Gbps which paves the way for future 100 Gbps wireless communications using high power high frequency RTD transmitters.

For more info contact: Edward Wasige Edward.Wasige@glasgow.ac.uk

# First transmission of advanced modulation formats based on an RTD-PD

The INESC team has successfully transmitted advanced modulation formats using electrical and optical subcarrier modulation of RTD-PDs for the first time. Figure 13 shows the measured experimental results in terms of the signal to noise ratio (SNR), as a function of the subcarrier frequency. Currently the performance is limited by the RTD phase noise especially for lower subcarrier frequencies, which can be compensated by means of injection locking the RTD oscillation carrier.

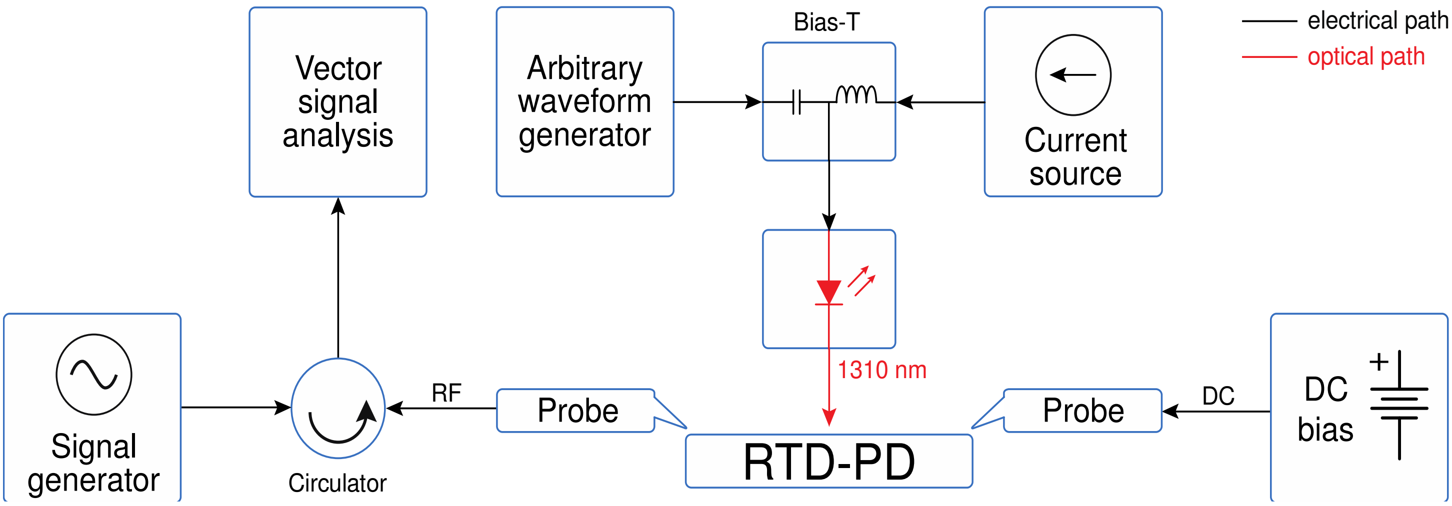



*Fig. 13: Diagram of the experimental set-up for transmission of advanced modulation formats with optical modulation using RTD-PDs.*

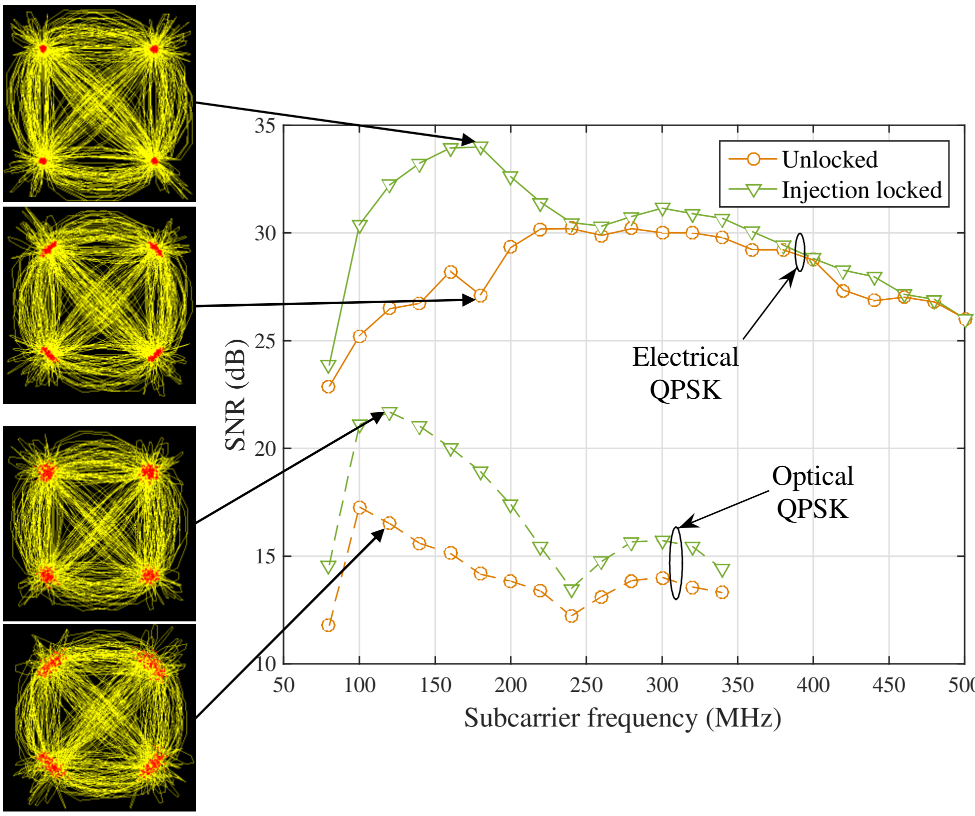



*Fig. 14: Constellation diagrams (left) and SNR versus subcarrier frequency obtained with 100 MBaud QPSK signal for locked and unlocked transmission experiments using electrical and optical QPSK.*

The constellation diagrams of the transmitted signals (shown on the left in Fig. 14) show the phase noise (visible in the constellation rotation) being completely compensated by injection locking when using electrical modulation (top) and a similar result using optical modulation (bottom) but with a lower SNR due to the losses associated with the RTD-PD optoelectronic conversion.

For more info contact:
Joana Santos Tavares
jst@inesctec.pt

# First RTD-PD based video transmission

By using the experimental set-up shown in Figure 15, based on an optically subcarrier modulated RTD-PD, the transmission of a video signal was achieved for the first time. The apparatus consisted of a laptop connected by HDMI to a DVB-T modulator and subsequent optical subcarrier modulation of the RTD-PD oscillating at around 13 GHz. The transmitted signals were demodulated by the TV DVB-T tuner and then both video and audio were correctly displayed on the TV, showing the feasibility of achieving optical modulation of the RTD-PD for the transmission of relevant data from an end-user perspective.

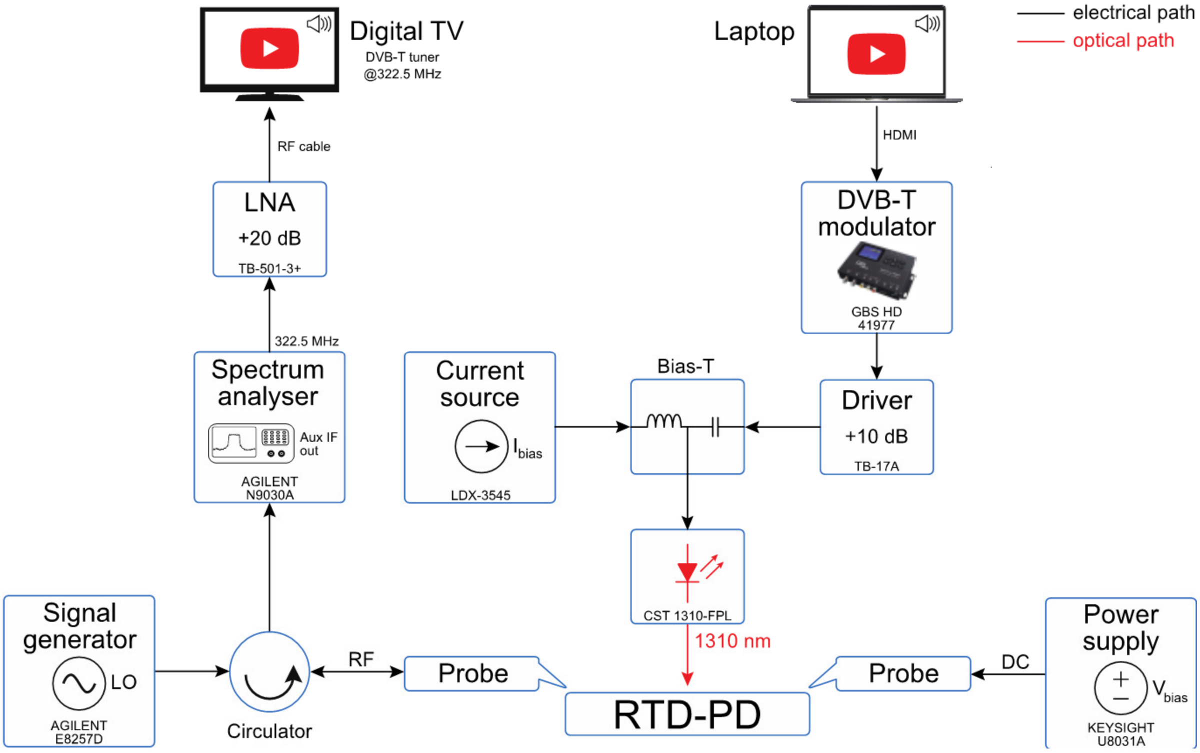



*Fig. 15: Diagram of the experimental set-up for DVB-T transmission with optical modulation* of an RTD-PD.

A video explaining the set-up is available https://www.youtube.com/watch?v=4gjaVpJQrkg

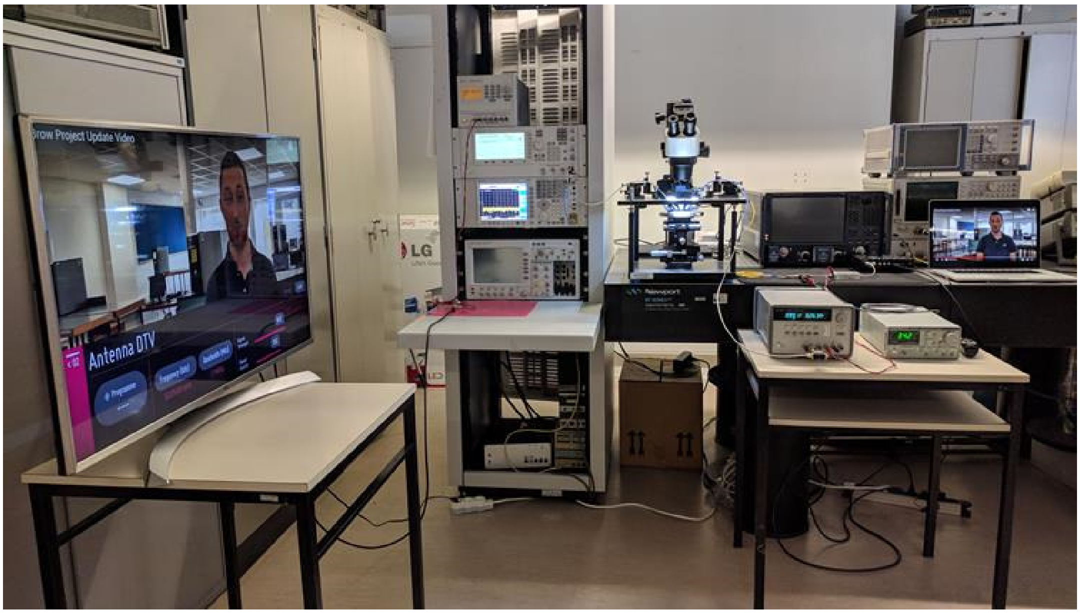


*Fig. 16: Photograph showing video transmission with optical modulation of RTD-PDs at INESC lab. An 8 min video of Dr. Luis Pessoa describing the detail of the apparatus is available online: see link above.*

For more info contact:
Luis Pessoa
lpessoa@inesctec.pt

# Unique mm-wave channel sounder capability

The newly procured PN-sequence based channel sounder available at TUBS has been used to perform channel measurements in the iBROW scenarios. Specifically spatial measurements at 10, 60 and 300 GHz have been made been made in order to investigate the applicability of device-discovery techniques based on measurements at different carrier frequencies in a variety of indoor environments from a small office to a lecture theatre (Fig. 17) and even a large auditorium. This enables the use of lower carrier frequencies for a rough estimation of the receiver and transmitter using low-gain antennas, while significantly reducing the number of required scans with the highly directive antennas at 300 GHz. The measurements and the concept were presented in London at EuCAP 2018. Fig. 18 shows an example of measured spatial characteristics at three carrier frequencies and two polarizations.

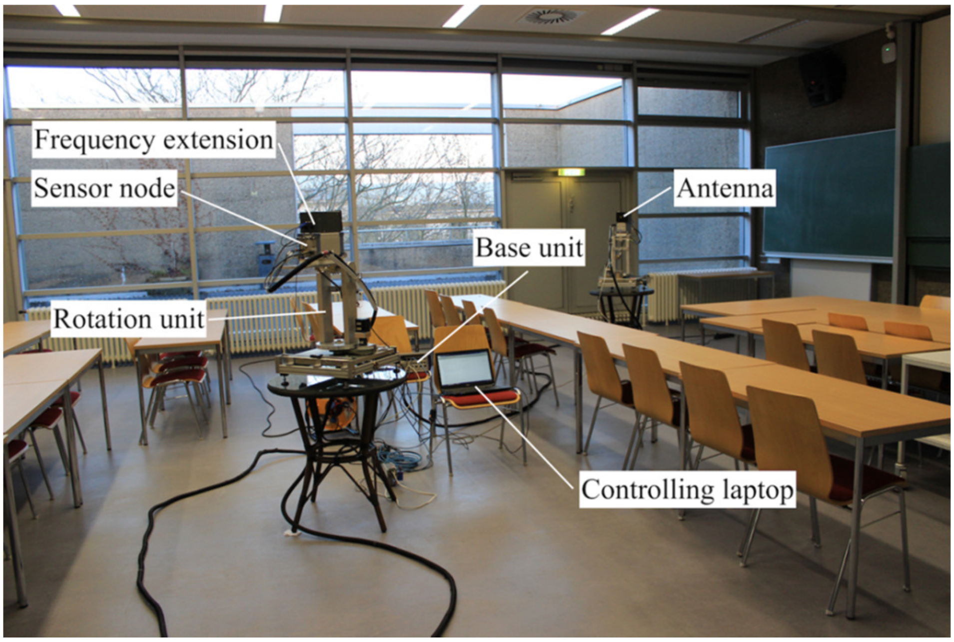



*Fig. 17: TUBS channel sounder during measurements of a lecture room*

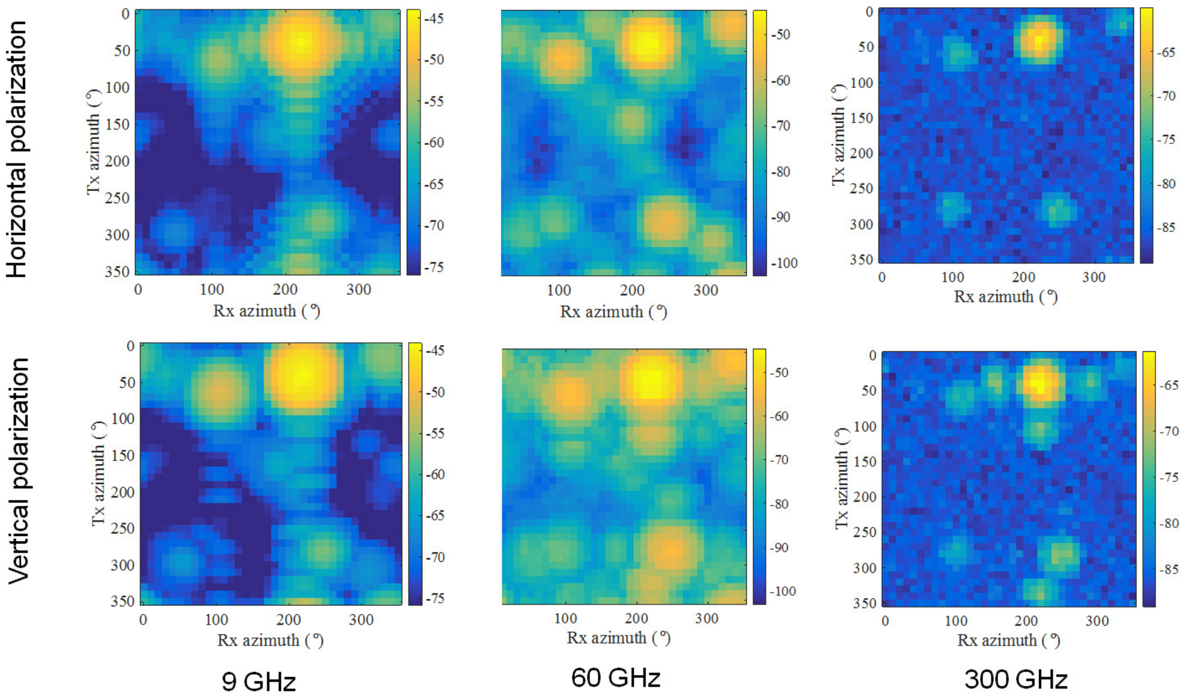



*Fig. 18: The results of measurements using the TUBS channel sounder showing spatial characteristics at three carrier frequencies and two polarizations.*

These measurements have enabled validation of the TUBS in-house ray launching algorithm and the investigation of THz massive MIMO concepts with iBROW partner Nokia.

For more info contact:
Johannes Eckhardt
Eckhardt@ifn.ing.tu-bs.de

## End user perspective on iBROW

NOKIA Bell Labs

One of the most important requirements for the communications industry sector in the coming decades, driven by consumer markets, is to provide systems and technology which can cope with the tremendous amounts of data which will need to be accessed and shared between users. As this data volume continues to grow, bandwidth is already becoming an increasingly precious and sparse resource. By opening the so-called THz-gap, new technologies promise access to an abundance of free spectrum, enabling those future applications which will require these tremendous data rates. One of the key technologies which has the potential to do just that is the resonant tunnelling diode (RTD). By taking advantage of the free unlicensed spectrum in the mm-wave/THz frequency bands, RTD-based technology is expected to set the foundations for a novel short-range wireless transceiver that will be ultra-broadband, energy efficient and compact in size such that it can be a building block for consumer portable devices and seamlessly integrated with high speed optical fibre networks, capable of addressing the ultra-broadband requirements. As a research partner within iBROW, Nokia has been involved in several activities, which are listed below:

**Usage scenarios & requirements**

- Contributions to the definition of the possible usage scenarios and suitable architectures for an RTD-based ultra-wideband mm-wave access system and its optical fronthaul network
- Contributions to the assessment of baseline studies including specifications referring to system-level requirements

**Device level characterisation**

- DC characterisation of RTD devices from other iBROW parters
    - Over 300 samples
- RF characterisation of iBROW electronic RTD (e-RTD) based sources
    - W-band samples

**Other activities**

- Participation in RF related discussions and EM simulation aspects with partners across the consortium
- Support in reviewing deliverables
- Contribution to dissemination and exploitation activities

**Future research**

- Study of concepts such as coherent RTD arrays, as an alternative for higher output power, which would allow in the long term the integration of RTD technology with optical fronthauling for future short haul and femtocells in wireless access scenarios.

As a final remark, all the above-listed activities reflect the interest shown by Nokia in RTD-based transceiver technology, and the potential it could offer in future communication networks. The involvement within the frame of the Horizon 2020 iBROW project has allowed Nokia to become acquainted with the potential, challenges and pitfalls of this promising new technology and look further into the means of developing system concepts tailored for a new generation of mm-wave transceivers, which represent a crucial building block in the coming generation of beyond-5G radio systems and network architectures.

For more info contact: George Hotopan george-roberto.hotopan@nokia-bell-labs.com

## iBROW contributions to standards

One of the goals of iBROW is to establish a framework for the uptake of RTDs by influencing the activities of standards bodies to ensure compatibility of planned and future standards with iBROW technology. iBROW has benefited greatly from the strong representation of Prof. Kürner and his colleagues at TU Braunschweig (TUBS) who are key players in the IEEE 802.15 Task Group 3d (100 Gbps Wireless) and the IG THz (THz Interest Group).

Through TUBS, iBROW has regularly reported its achievements to IEEE 802.15 IG THz TG3d, especially in the areas of indoor channel measurements and angle-of-arrival estimation at 300 GHz with high gain antennas on both sides of the link. These contributions form an important basis for a future task group for standardizing amendments for WLAN-type applications and iBROW has had a strong influence on the most important current international standards work in THz communications.

→ As a result of this activity, the new IEEE Std. 802.15.3d-2017 – the world-wide first standard for wireless communication at 300 GHz was strongly based on iBROW-based proposals.

For more info contact:
Thomas Kürner Kuerner@ifn.ing.tu-bs.de

## iBROW spin-off projects

iBROW has directly contributed to several new projects which will continue the work on RTDs and THz communications, including the emphasis on standards.

**ThoR (Horizon 2020)** http://thorproject.eu

*TeraHertz end-to-end wireless systems supporting ultra high data Rate applications*

ThoR is a joint EU-Japan project to provide technical solutions for data networks beyond 5G based on 300 GHz RF wireless links. ThoR builds on the new IEEE Std. 802.15.3d-2017 (see above) using state-of-the-art chip sets and modems operating in the standardized 60 and 70 GHz bands aggregated on a bit-transparent 300 GHz RF wireless link with >100 Gbps real-time data rate capacity.

**TERAPOD (Horizon 2020)** http://terapod-project.eu

*TeraHertz based ultra-high bandwidth wireless access networks*

TERAPOD will demonstrate the feasibility of ultra high bandwidth wireless access networks operating in the THz band. It will focus on an end-to-end demonstration of the THz wireless link in a data centre proof of concept deployment.

**WiPHi (Innovate UK)** www.cstglobal.uk/projects/wiphi

*High performance wireless/photonic interfaces for 60 GHz radio over fibre applications*

WiPHi (CST/Optocap/University of Glasgow) will integrate InP RF devices and optical sources as microwave photonic interfaces to exploit the framework and standards available at 60 GHz (V-band).

For more info contact: Bruce Napier bruce@vividcomponents.co.uk