Innovative ultra-**BRO**adband ubiquitous **W**ireless communications through terahertz transceivers

iBROW

Mar-2017

Presentation outline

- Project key facts
- Motivation
- Project objectives
- Project technology
  - RTDs
  - RTDs on silicon
  - User scenarios
- Summary

iBROW key facts

- Horizon 2020 project funded by the European Commission
  - ICT-6: Smart optical and wireless network technologies
- Budget: *c.* 4 M€
- Eleven partners
  - 2 large industrial, 3 SME, 3 R&D, 3 academic
- Start date: 01-Jan-2015
- Duration: 36 months
- Coordinator: University of Glasgow
- Project public website: www.ibrow-project.eu

Consortium

University of Glasgow	Academic	RTD research (device & circuit design, process development)
NOKIA Bell Labs	Large Industrial	Component manufacturer (optical/wireless network equipment)
cea	R&D	III-V on Si wafer bonding research
Compound Semiconductor Technologies	SME	Component manufacturer (III-V based devices)
III-V lab	R&D	III-V on Si research (design, processing and validation)
INESCTEC	R&D	Wireless/optical communications research
IQE Silicon Compounds	Large Industrial	Wafer manufacturing (III-V on Si epitaxial growth)
optocap	SME	Component manufacture (packaging solutions)
Technische Universität Braunschweig	Academic	mm-wave & THz wireless communications research
UAlg Universidade do Algarve	Academic	RTD research (design, modelling and characterisation)
VIVID Components	SME	Project management

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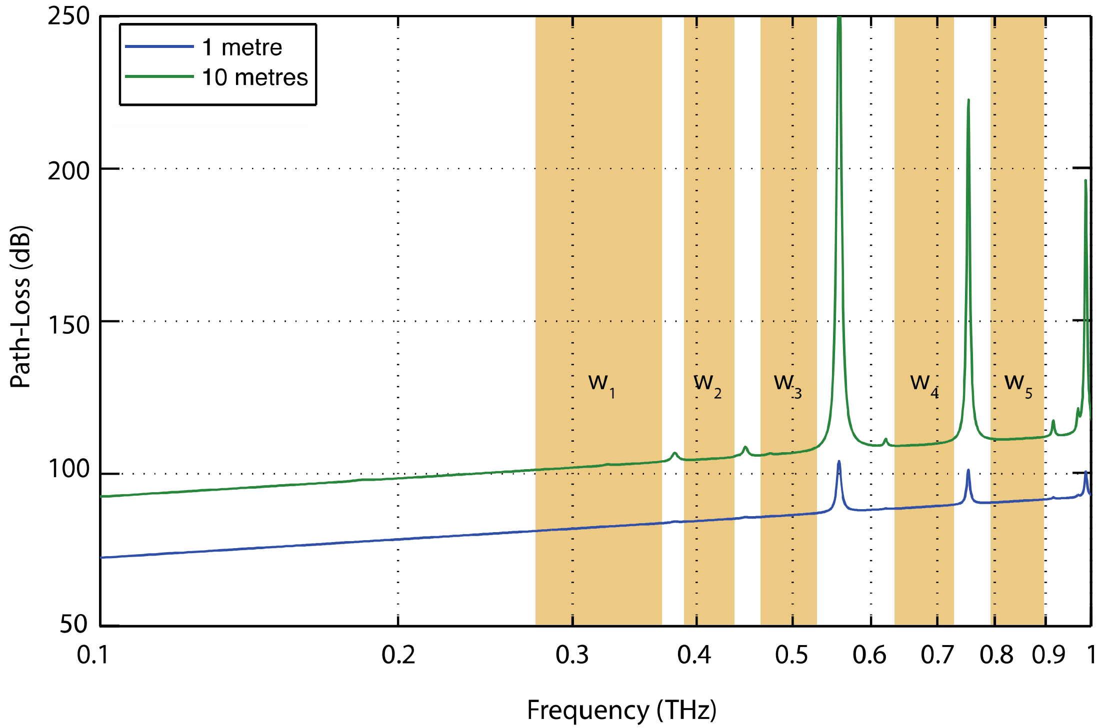
Motivation 1

- Traffic from wireless devices soon expected to exceed that from wired devices
- High-resolution video will account for 69% of all mobile data by 2018, up from about 53% in 2013
- Wireless data-rates of multiple tens of Gbps will be required by 2020
- Demand on short-range connectivity

Motivation 2

- Significant previous R&D effort in complex modulations, MIMO and DSP up to 60 GHz
- Spectral Efficiency (SE) limits
  - Achieving 10s of Gbps in current bands will require high SE



→ Solution?

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Project Objective

Develop a novel short range wireless communication transceiver technology that is:

- Energy-efficient
- Compact
- Ultra-broadband
- Seamlessly interfaced with optical fibre networks
- Capable of addressing predicted future network usage needs and requirements.

Project Ambition

- Demonstrate **low cost and simple** wireless transceiver architectures that can achieve at least **10 Gbps** by exploiting the mm-wave and THz frequency spectrum
  - Long term target **100 Gbps.**

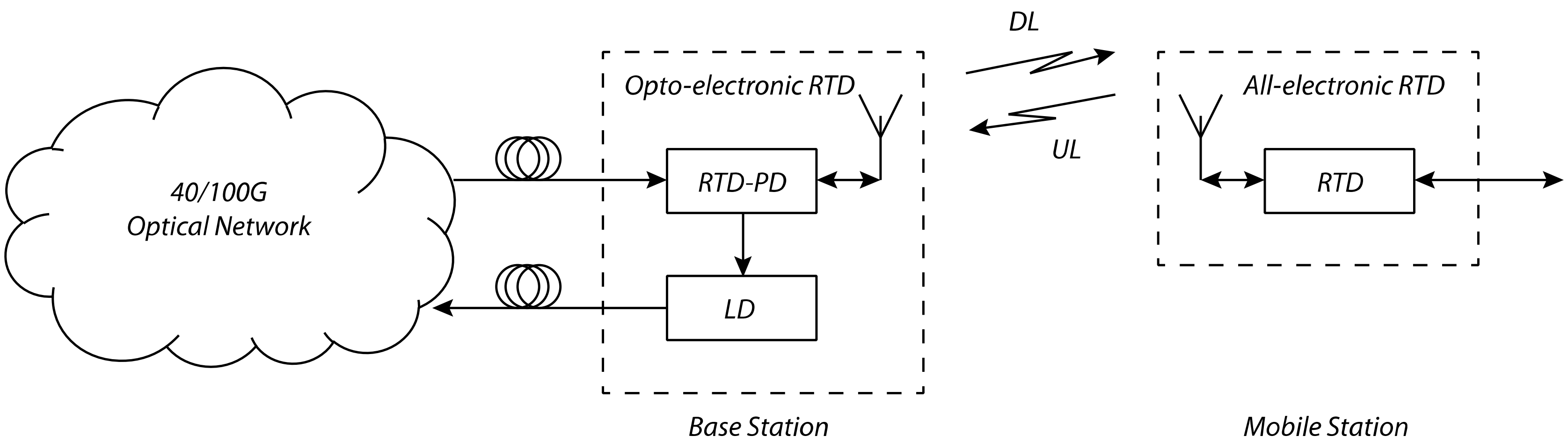
- Demonstrate **integrated semiconductor** emitters & detectors having enough power/sensitivity for exploiting the full potential of THz spectrum, and allowing for **seamless fibre-wireless interfaces**.

- Demonstrate a **highly compact** technology suitable for integration into battery constrained **portable devices**.

- Develop an **energy efficient and low power** wireless communications technology addressing the reduction of the ICT carbon footprint imputed to communication networks.

How?

- Exploit Resonant Tunnelling Diode (RTD) transceiver technology



- All-electronic RTD for integration into cost-effective wireless portable devices
- Opto-electronic RTD (RTD-PD-LD) for integration into mm-wave/THz femtocell basestations

iBROW methodology

- Baseline studies to establish application scenarios
  - RTD technology options
  - Channel modelling & communications architectures
- Monolithic realisation of high power
  - 10 mW @ 90 GHz
  - 1 mW @ 300 GHz
  - Low phase noise sources

  → Ultimately on a III-V on Si platform
- Monolithic realisation of high responsivity (>0.6 A/W) and high sensitivity RTD-photodiode detectors
- Hybrid integration of RTD-PD and laser diode optical-wireless interface and its characterisation
- Evaluation of wireless-wireless links and optical-wireless links
- Test bed demonstrator

Consortium organisation

Electronic RTD design

University of Glasgow

III-V on silicon

IQE Silicon Compounds

III-V lab

cea

Packaging

optocap

Communications

INESCTEC

Technische Universität Braunschweig

Optoelectronic RTD Design

University of Glasgow

UAlg Universidade do Algarve

Compound Semiconductor Technologies

End-User

NOKIA Bell Labs

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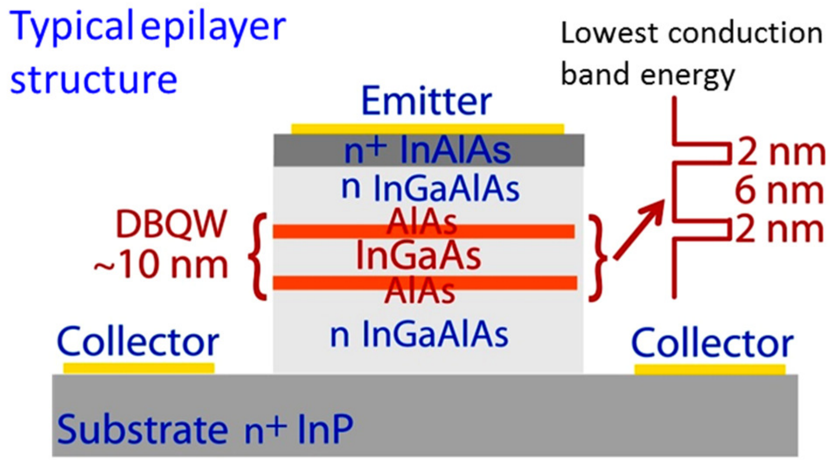
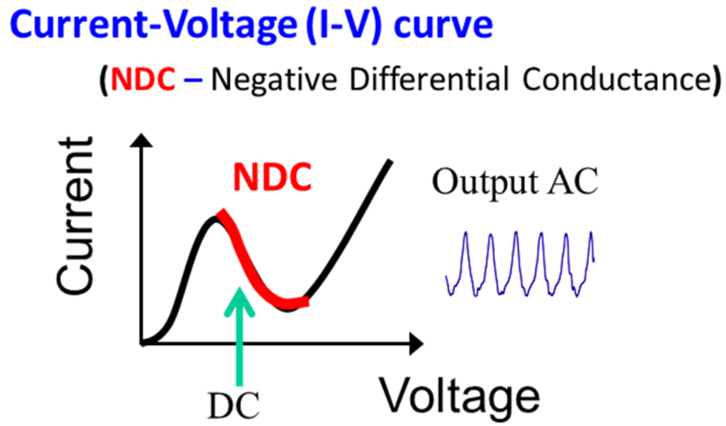
What is an RTD?

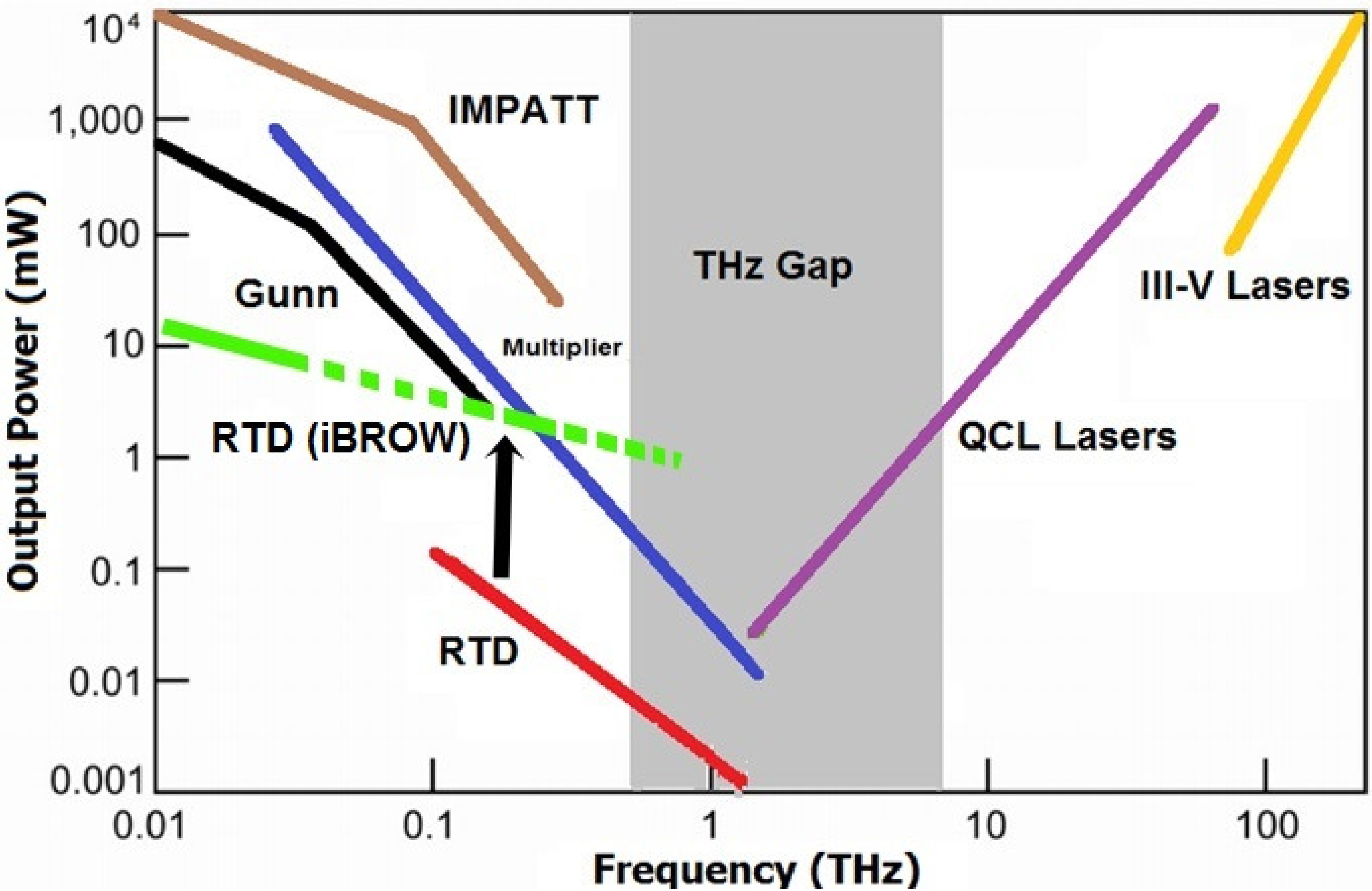
- RTD first demonstrated in 1974
- Consists of vertical stacking of nanometric epitaxial layers of semiconductor alloys forming a double barrier quantum well (DBQW)



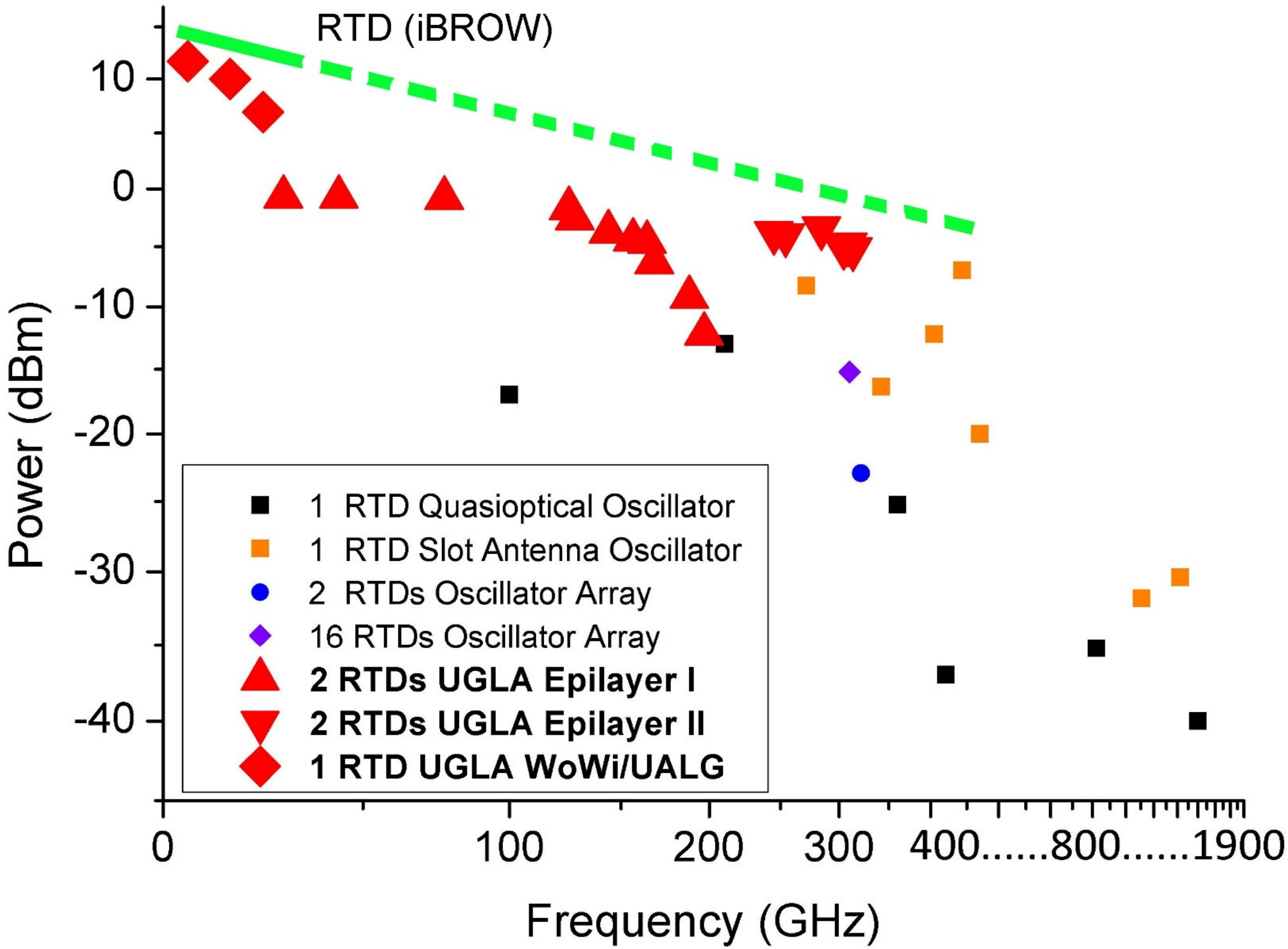
- Oscillations can be controlled by either electrical or optical signals
- Highly nonlinear device
  - Complex behaviour including chaos
- Exhibit wideband negative differential conductance (NDC)



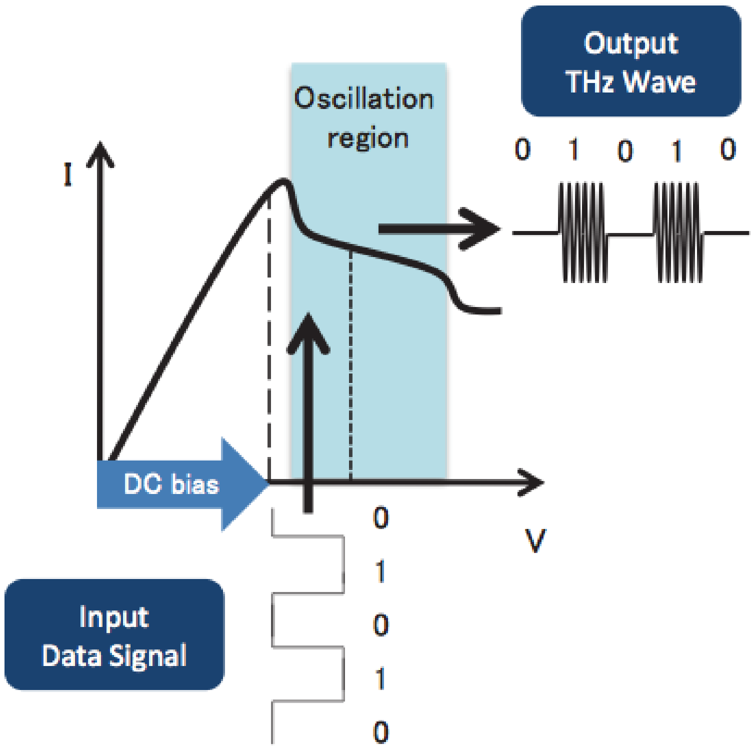
RTDs vs Other Technologies

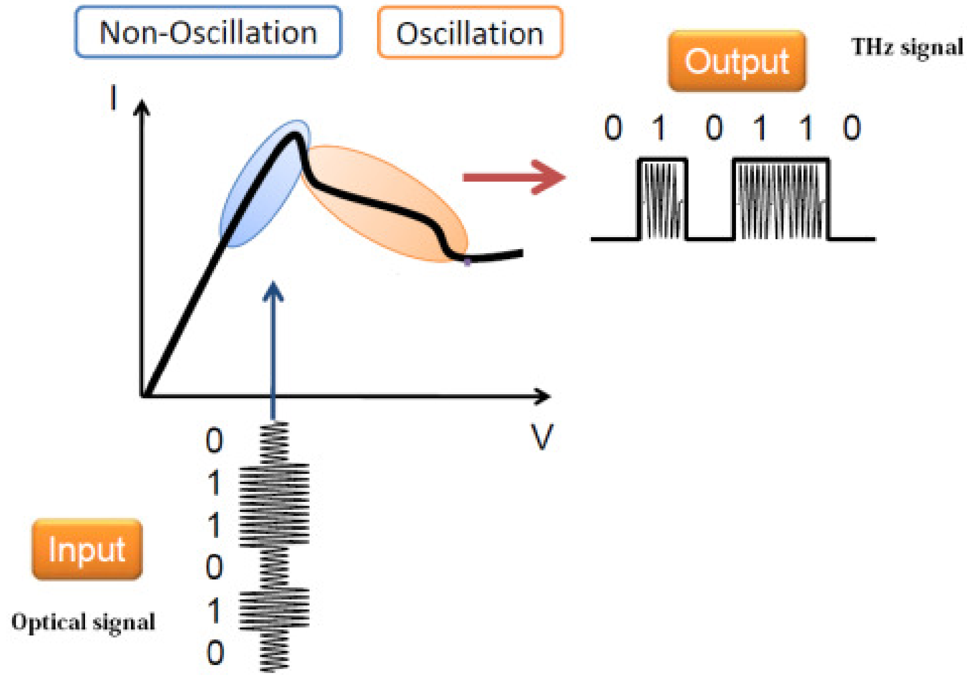


State-of-the-art RTDs



Taking advantage of RTD–based communications: On-off keying modulation





- All-electronic RTD
- Optoelectronic RTD-PD

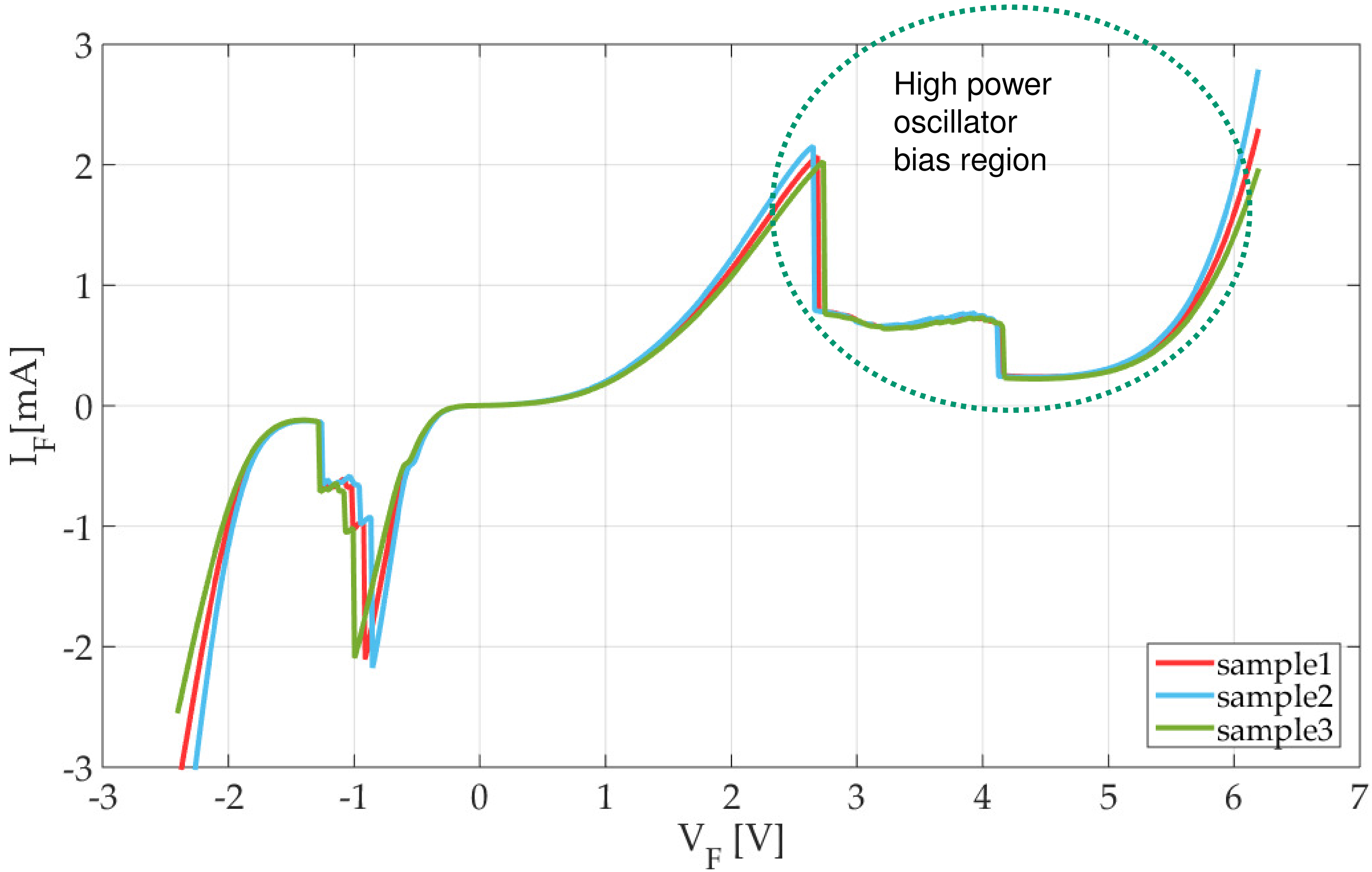
iBROW RTD THz source specs

- Monolithic realisation of high power sources
  - 10 mW @ 90 GHz
  - 5 mW @ 160 GHz
  - 1 mW @ 300 GHz
  - Low phase noise sources

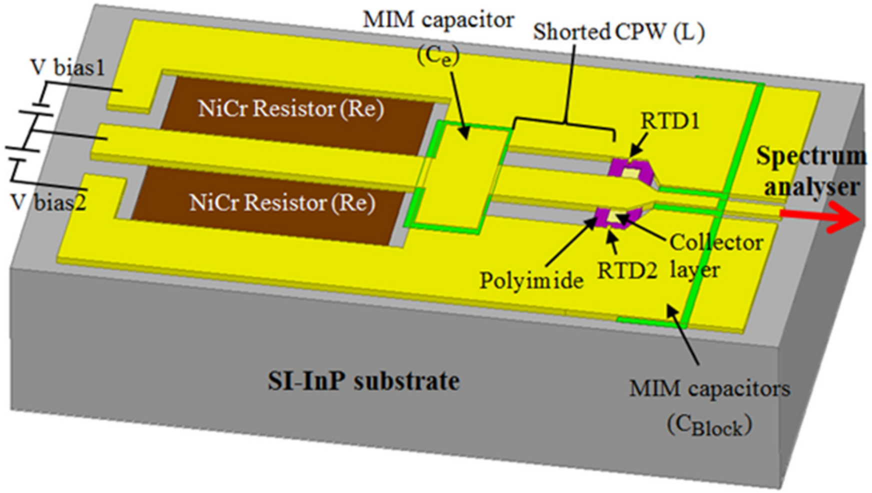
  → Ultimately on a III-V on Si platform

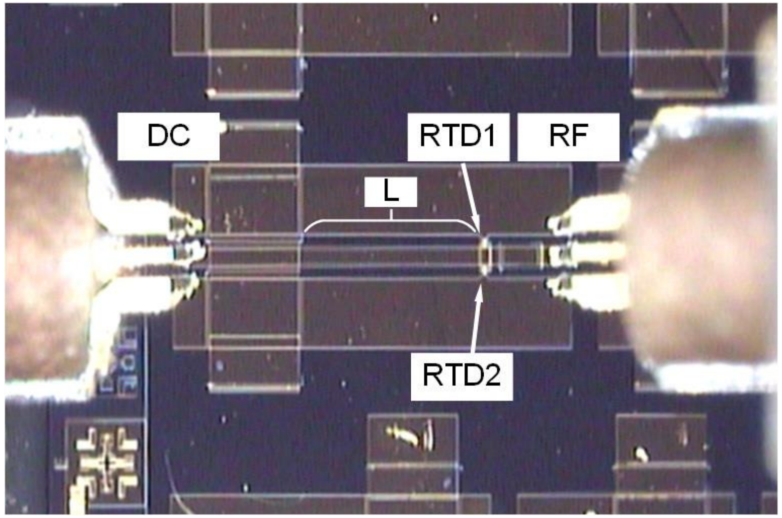
- **Other iBROW tasks**
- RTD photodetectors with high responsivity and sensitivity
- Evaluation of wireless-wireless links and optical-wireless links
- Test bed demonstrator

mW RTD oscillators

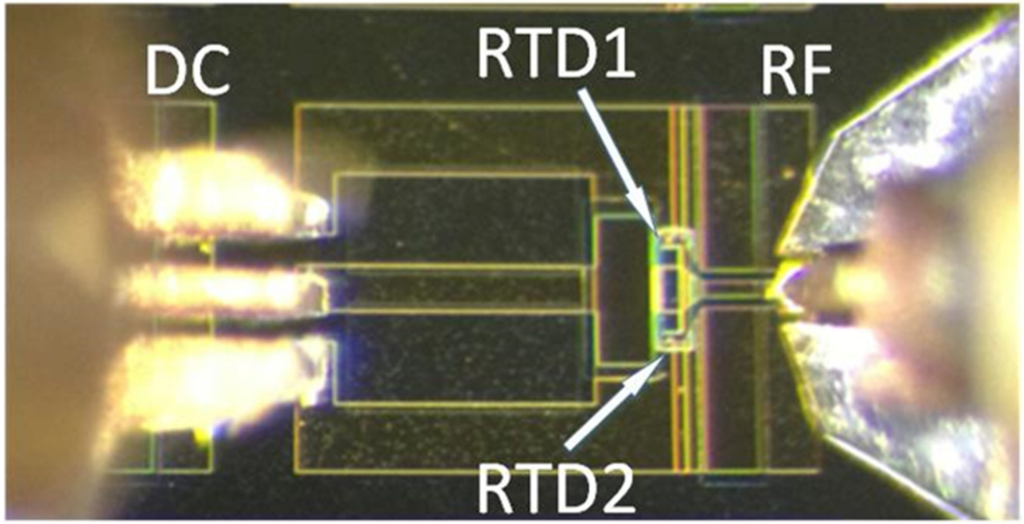


2-RTD oscillator layout



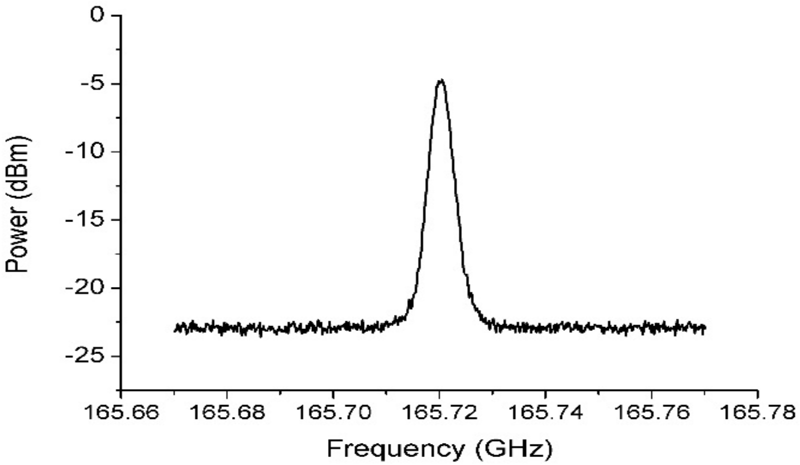


165 GHz oscillator

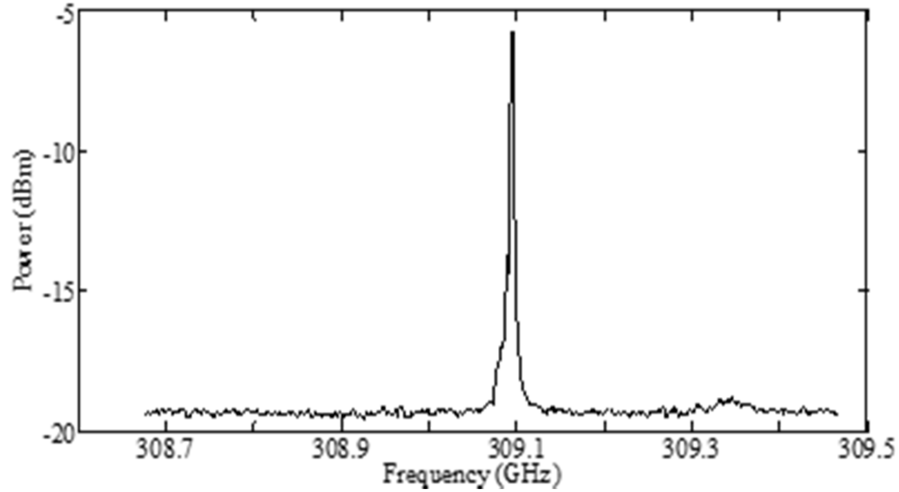


300 GHz oscillator

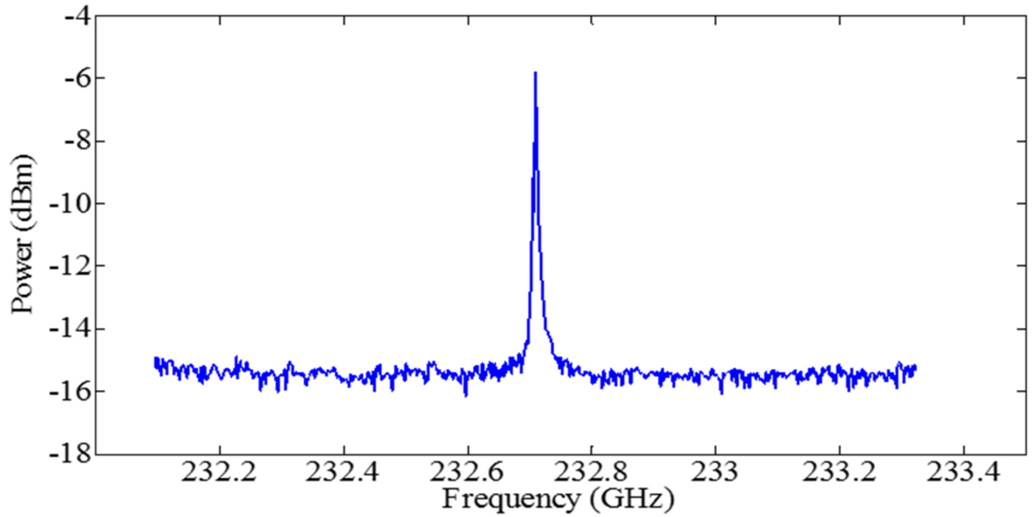
Measured spectra examples



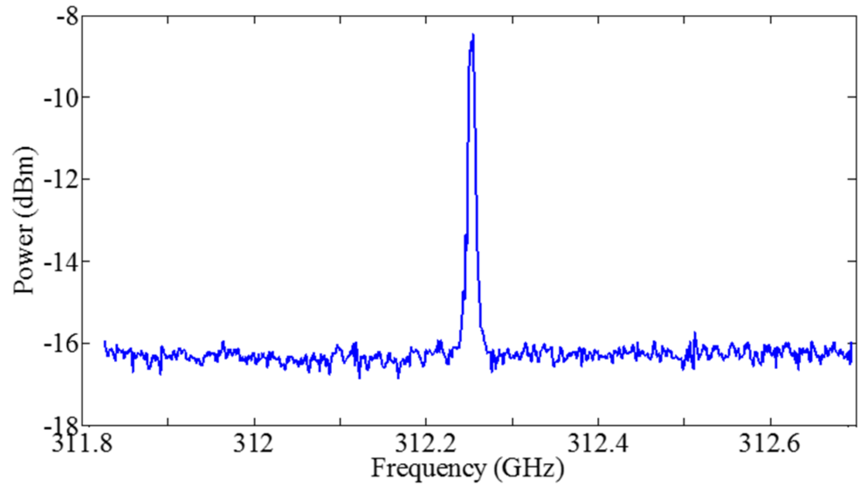
oscillator



309 GHz RTD oscillator

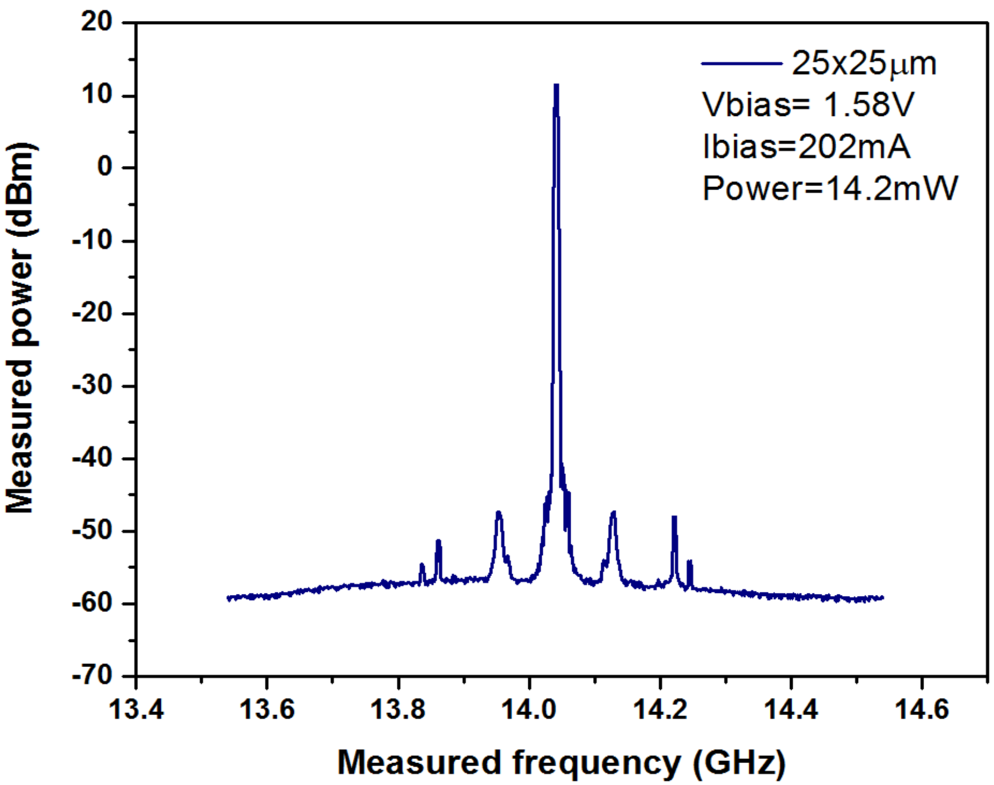


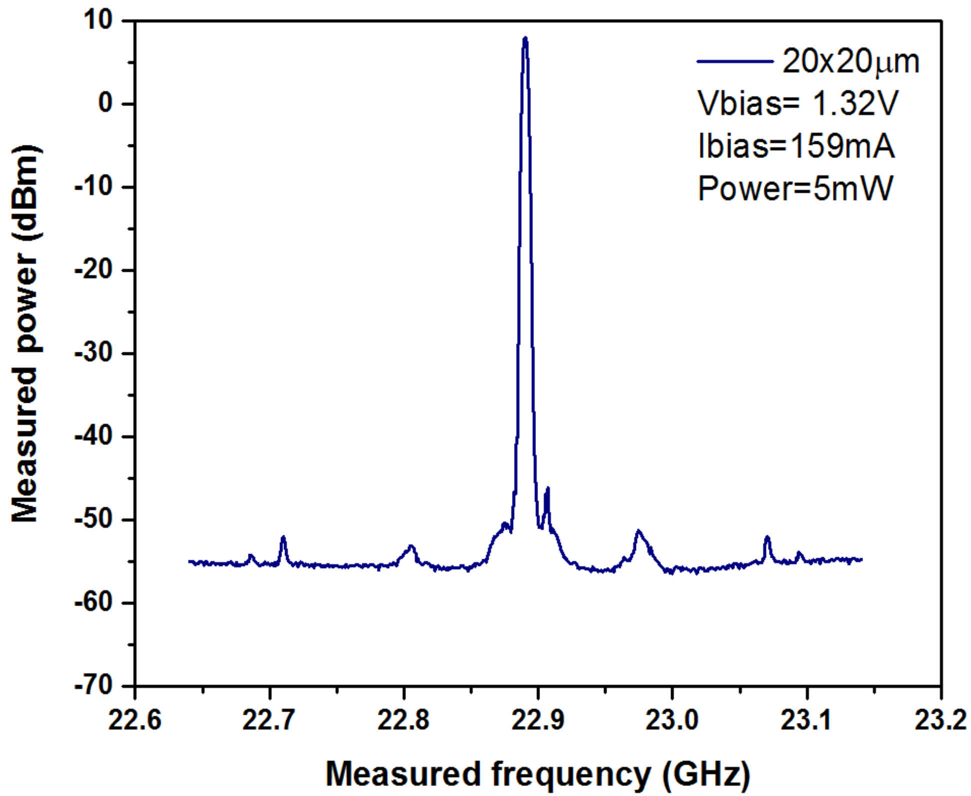
232 GHz RTD oscillator



312 GHz RTD oscillator

High power RTD-PD oscillators





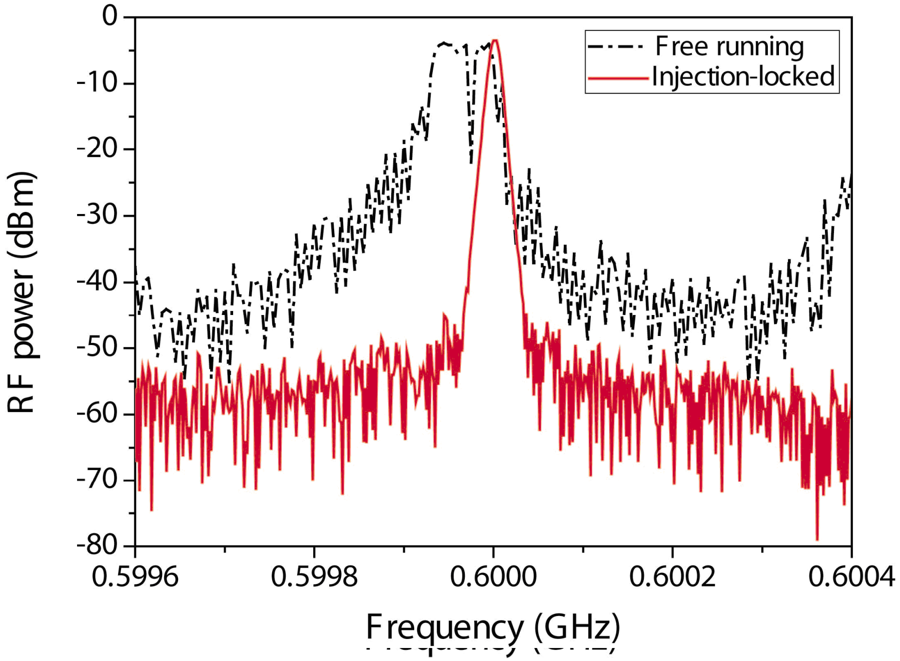
14.2 mW @ 14 GHz

5 mW @ 23 GHz

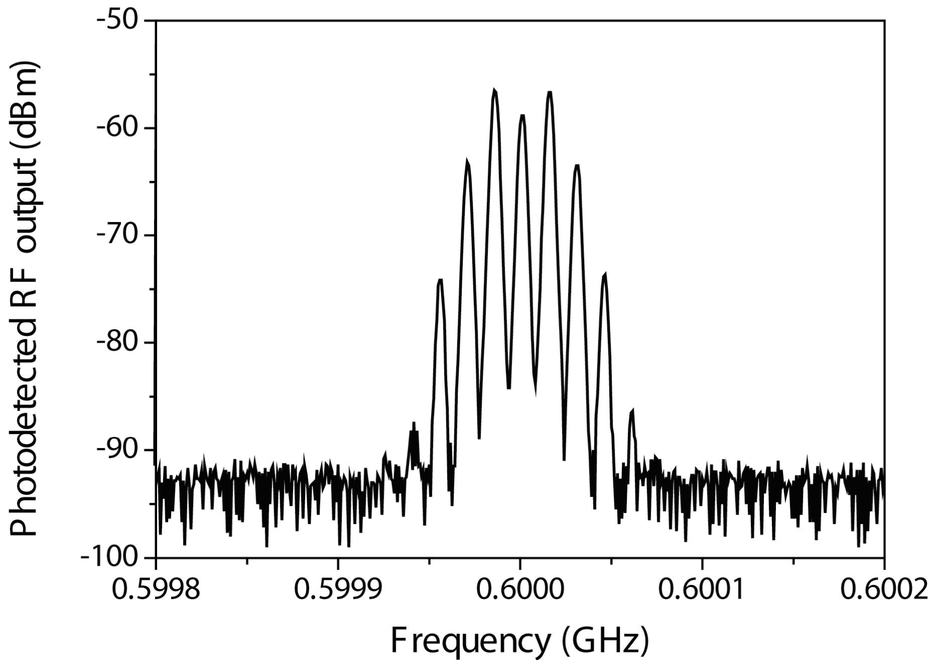
RTD-PD optical injection locking

- The photo-generated current is amplified by the NDR
- Optical locking of the RTD oscillations

Optical injection locking



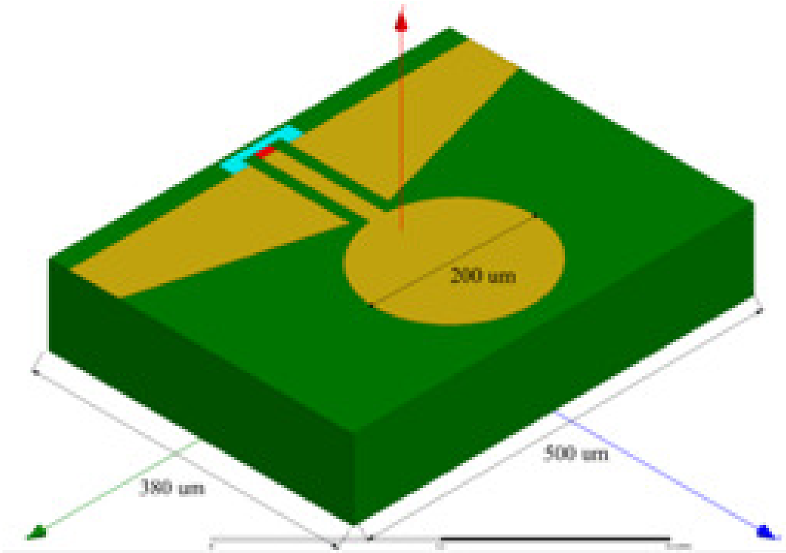
Optical phase-locking

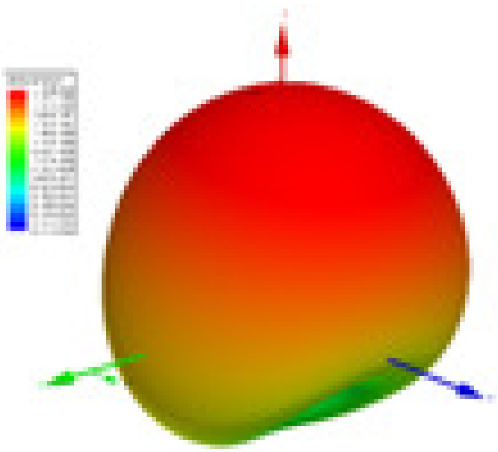


- RTD-PD oscillations follow the phase of the RF optical sub-carrier signal
- This behavior was demonstrated in digital communication schemes including PSK digital modulation *e.g.* RZ-DPSK.

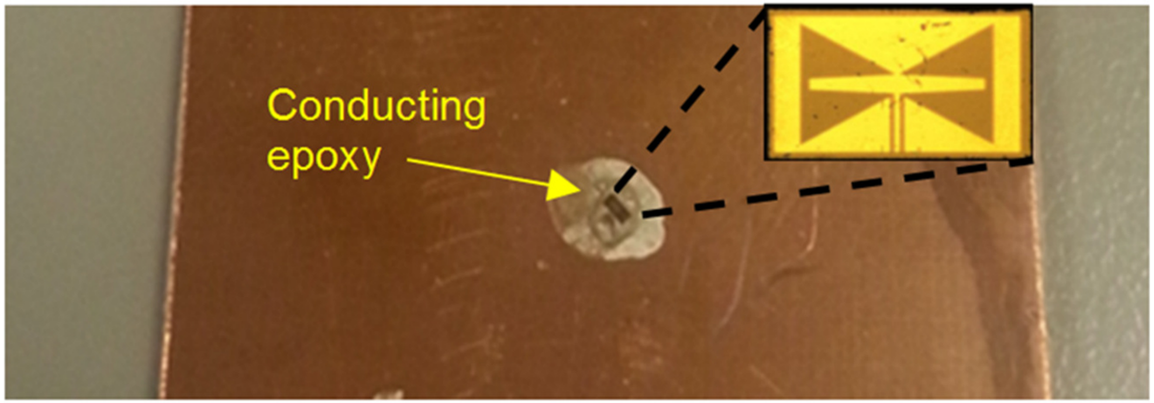
Antenna integration

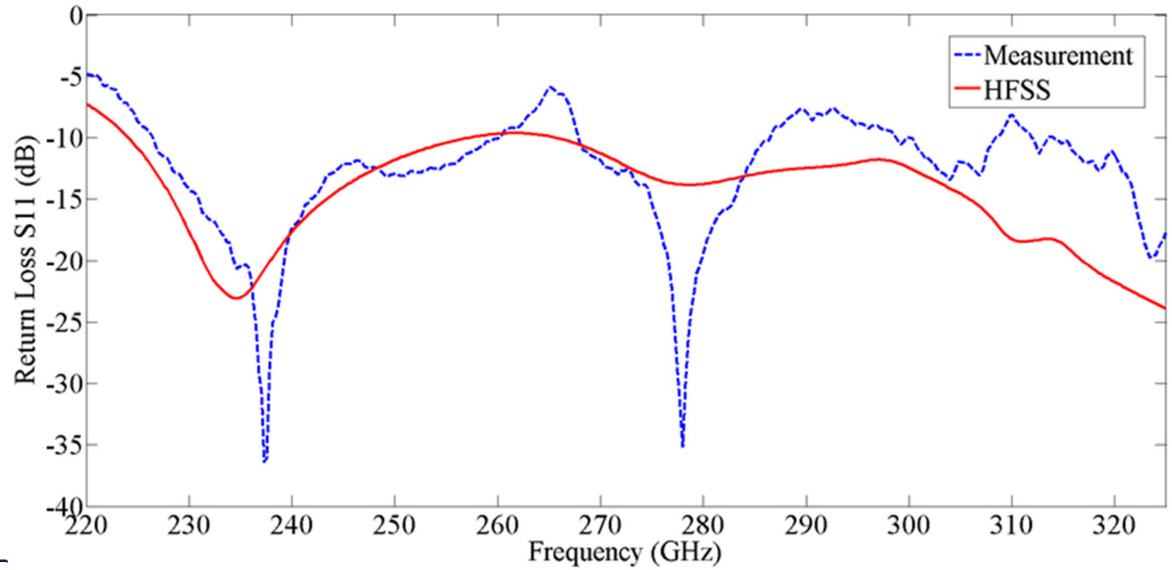
Monopole antenna



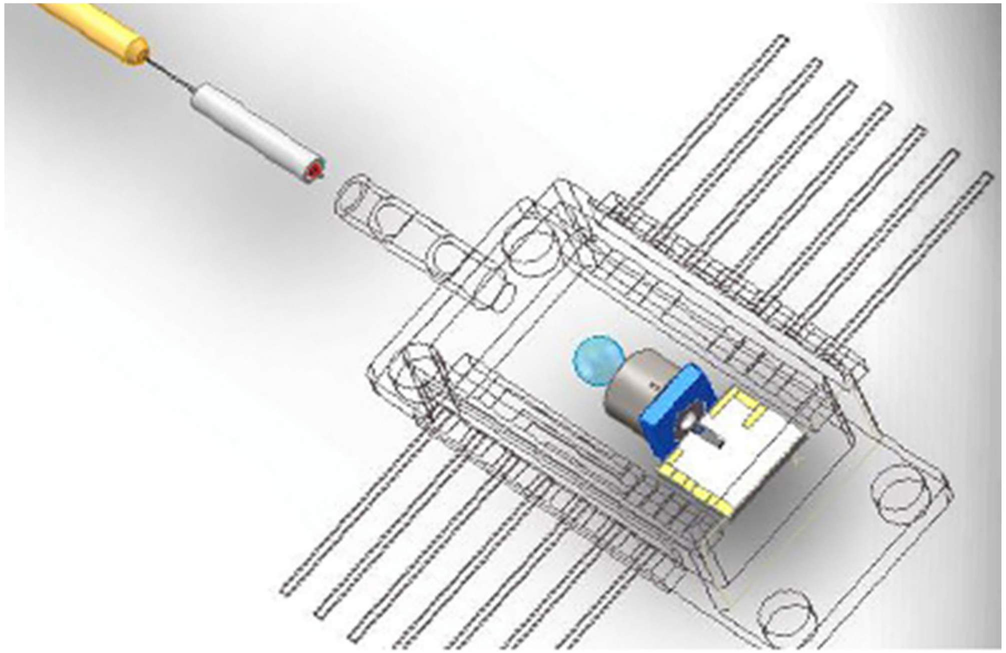


Diced and ground slot bow-tie with tuning stub





RTD Packaging



- **Thermal, mechanical and optical packaging design**
- Hermetic sealing
- Lensed fibre coupling

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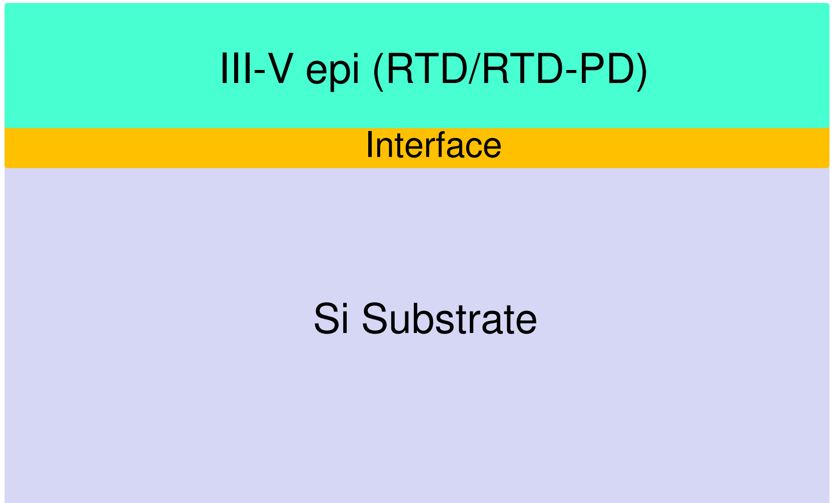
III-V on silicon

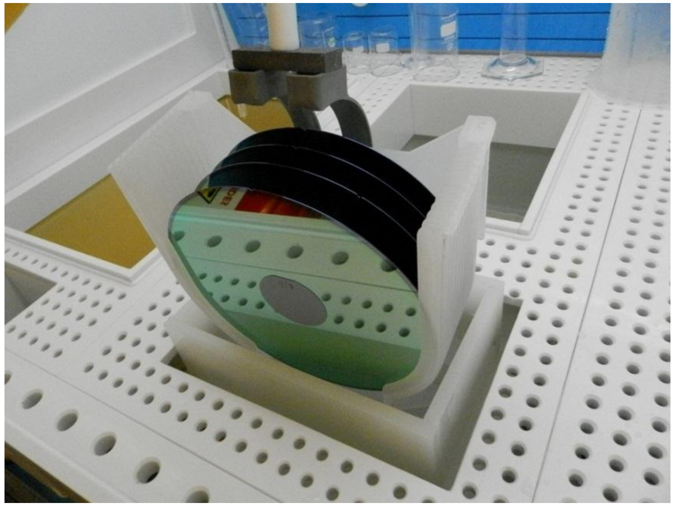


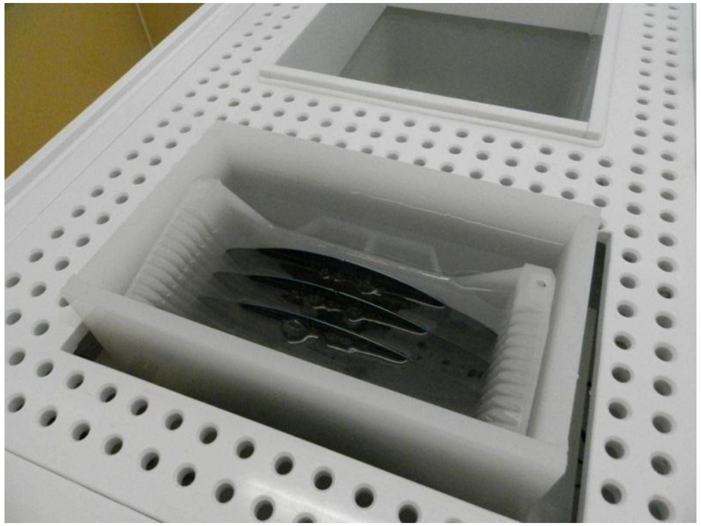
- **Direct growth** of III-V RTD layers on a Si substrate
- **Direct wafer bonding** between III-V & Si substrates
  - Potential for large diameter **≥200 mm wafers**
  - Integration with CMOS, etc.

III-V on silicon

- Conventional hybrid approaches:
  - Wire-bonded or flip-chip multi-chip assemblies
  - Suffer from variability and relative placement restrictions
- **Direct hetero-epitaxial growth**
  - III-V on a GeOI/Si template
  - Exploit previous knowledge from the DARPA COSMOS programme
- **Direct wafer bonding**
  - Process III-V surface to achieve bonding at room temperature
- Proved effective in solving mismatch problems
  - Lattice constant
  - Thermal expansion coefficient.

III-V on Si: Wafer bonding



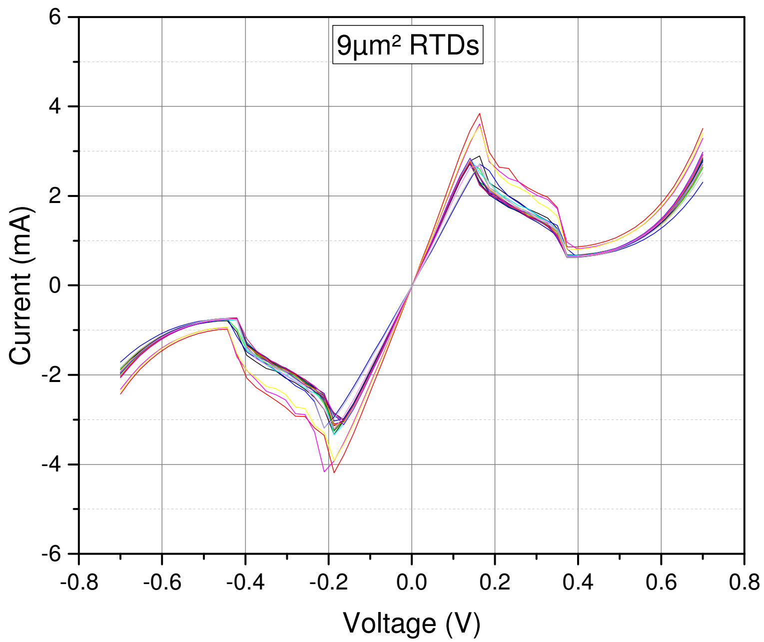


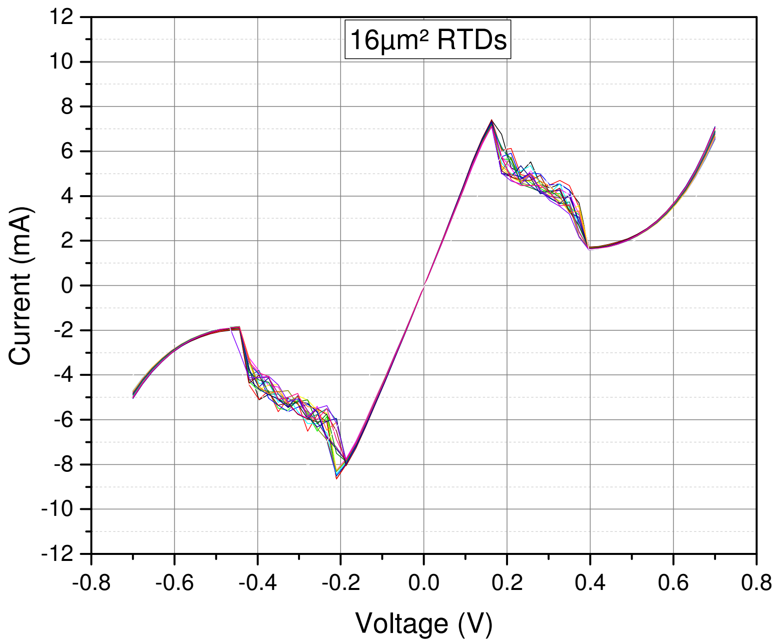
Bath in vertical position

Wafer before and after InP etching

- RTD epitaxial layer structure transferred to a Si host substrate via wafer bonding and subsequent InP removal
- 75 mm wafers obtained by laser dicing

III-V on Si: Wafer bonding





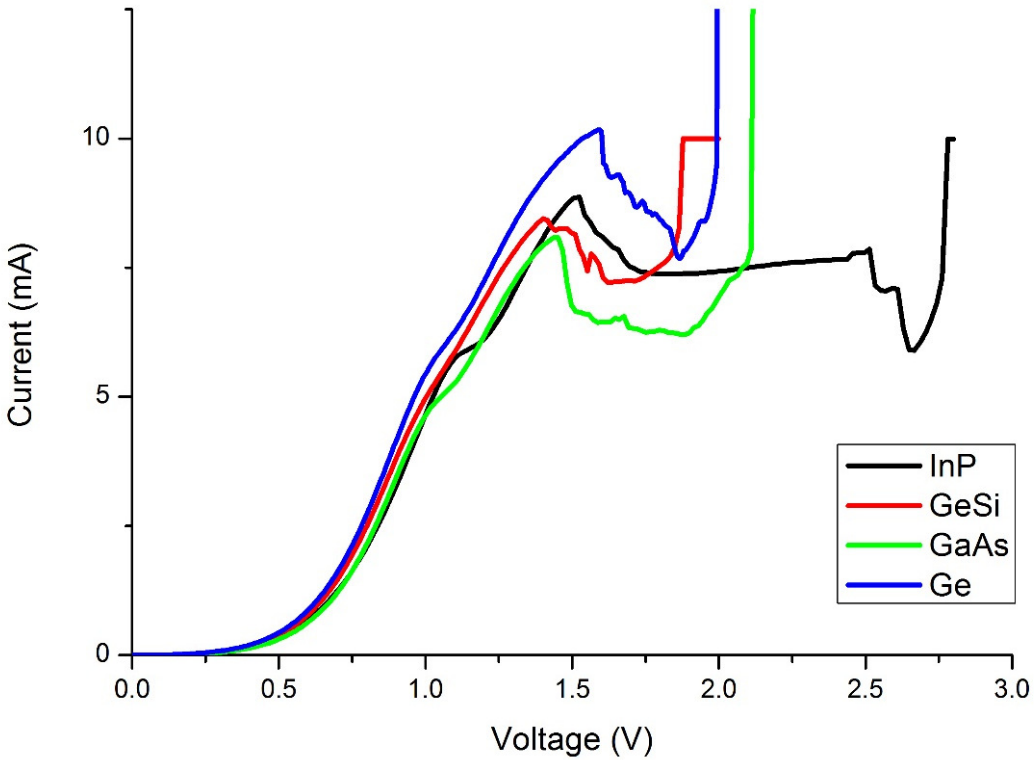
Device characteristics of RTDs on Si

- High fabrication yield
- Clear NDR in forward as well as in reverse bias

III-V on Si: direct growth

RTD surface on InP substrate, roughness ~ 2.4 nm

RTD surface on Ge/Si substrates, roughness ~ 7 nm



Device characteristics of 9 μm^2 devices on InP, GaAs, Ge, and Ge-Si substrates

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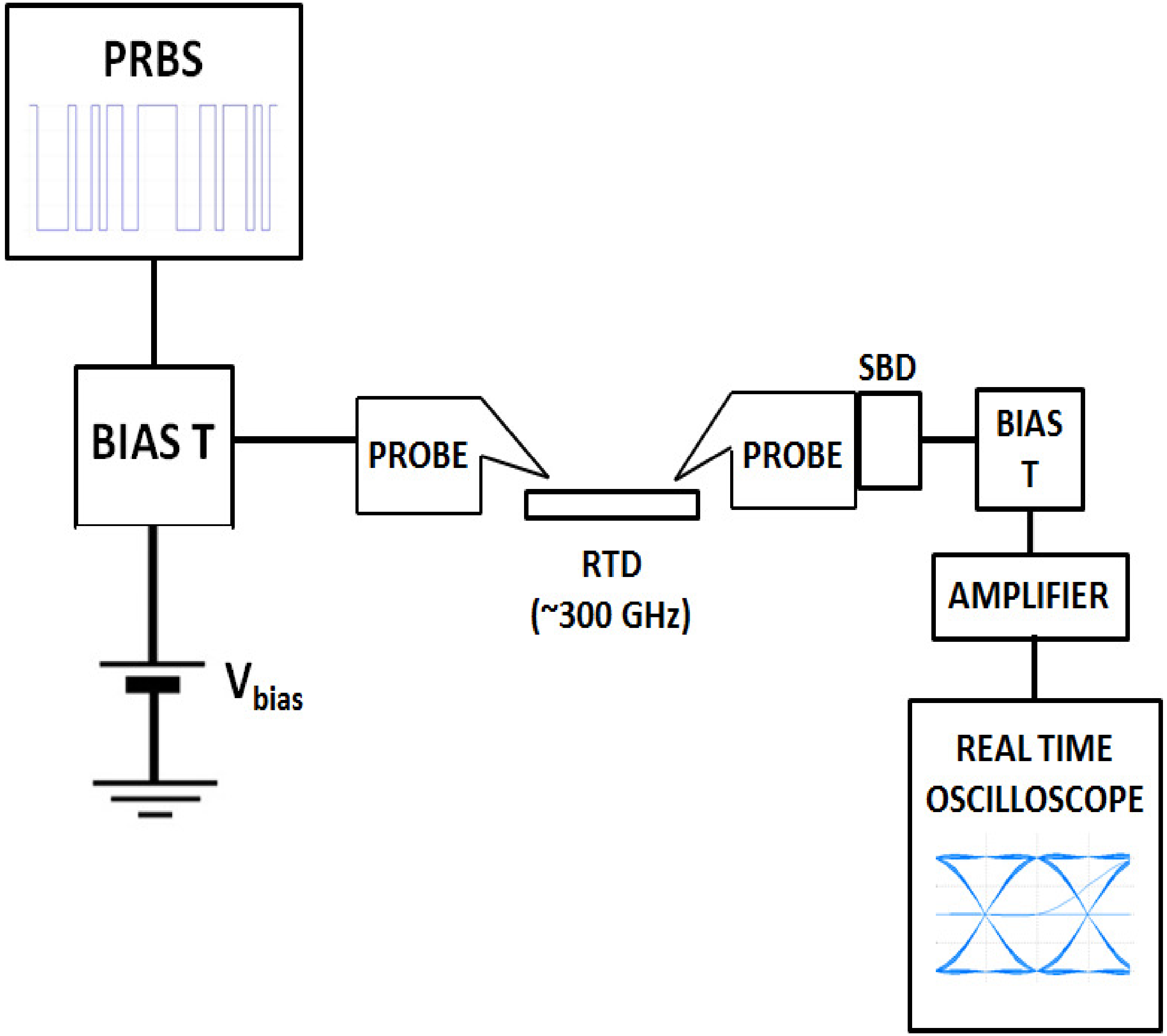
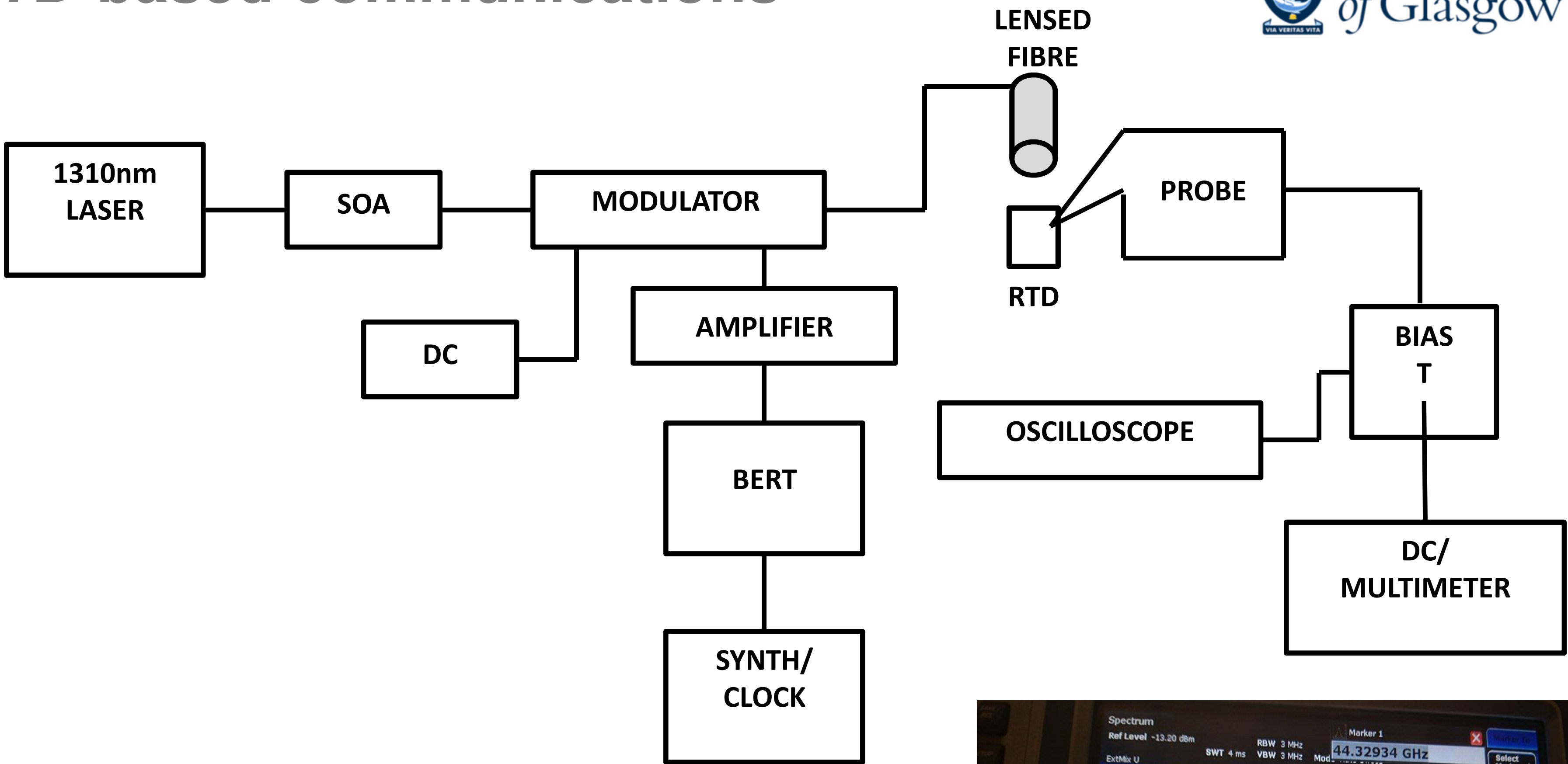
RTD-based communications

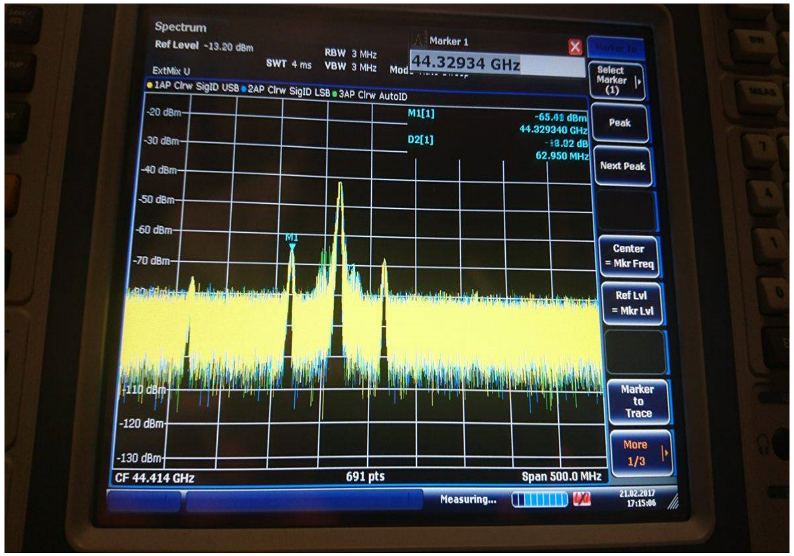


- Data transmission can be achieved using an electronic RTD oscillating at ~300 GHz
- A data pattern can be combined with a DC bias and sent to the RTD
  - Signal can be detected using a Schottky barrier diode (SBD) connected to a high speed probe
- Eye diagrams can be captured to show a visual representation of the received data pattern

RTD-based communications

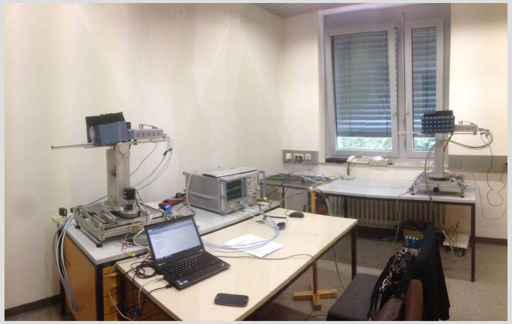


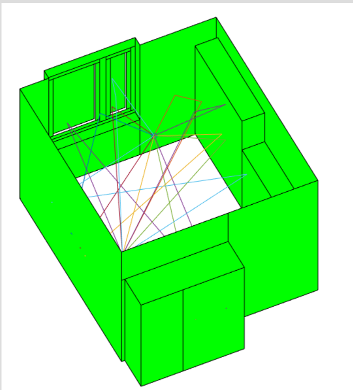
- RTD-PDs can be used as optical data photo-detectors
  - Data can be viewed as eye diagrams
- RTD-PD oscillators react to optical data signal
  - The signal can be used to move the RTD in and out of NDR
  - It can also directly modulate the RTD



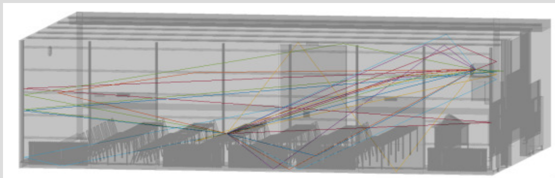
Scenarios for measurements and simulation

Small Office

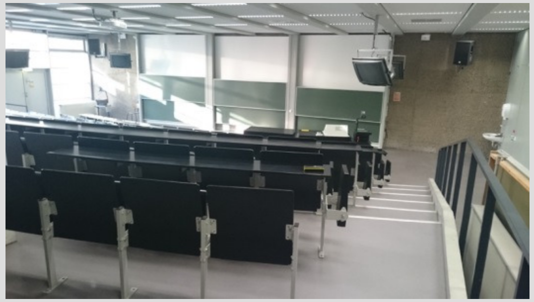


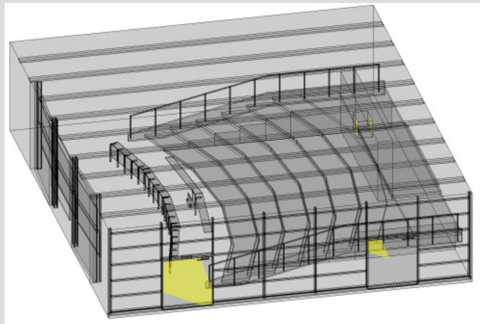


Lecture Hall

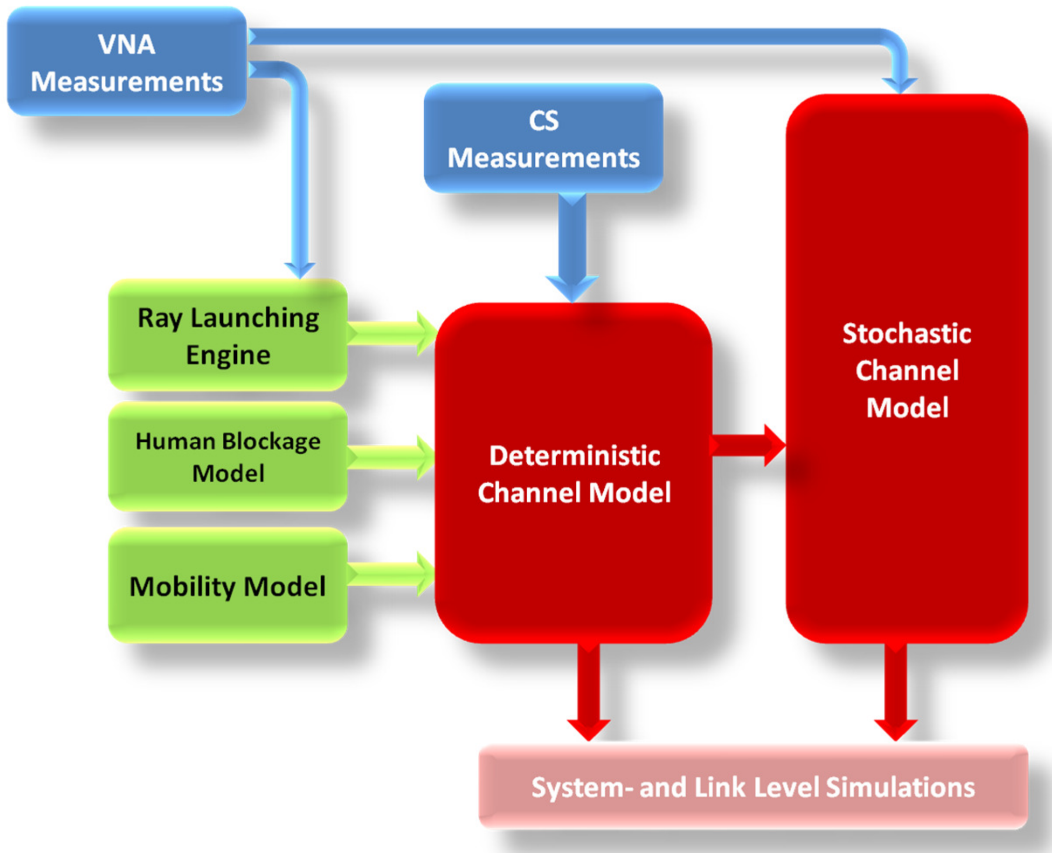


Auditorium





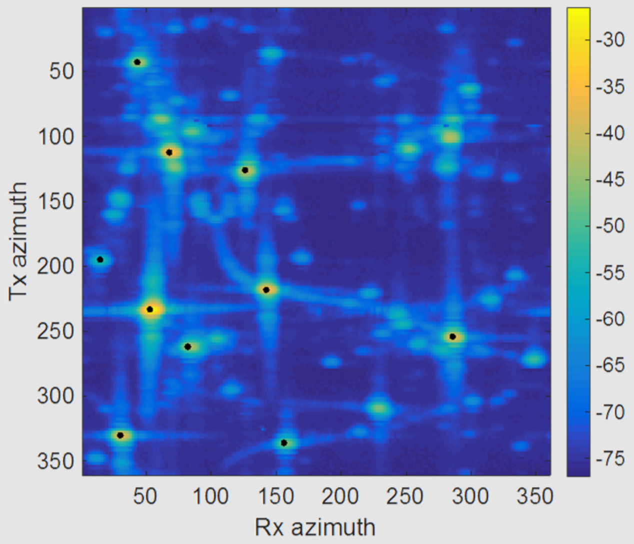
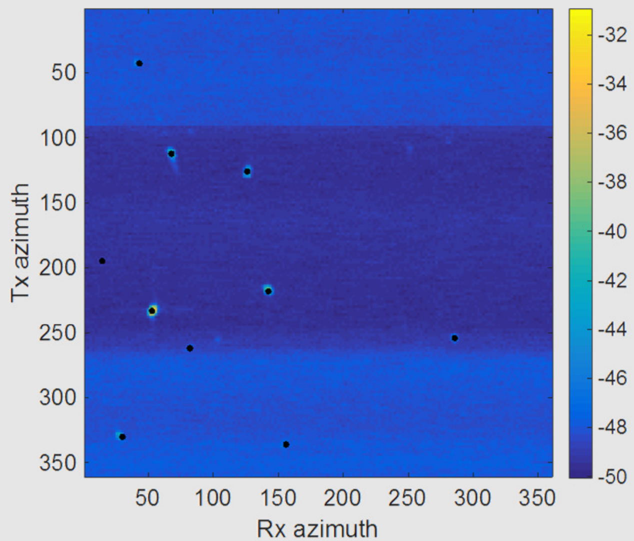
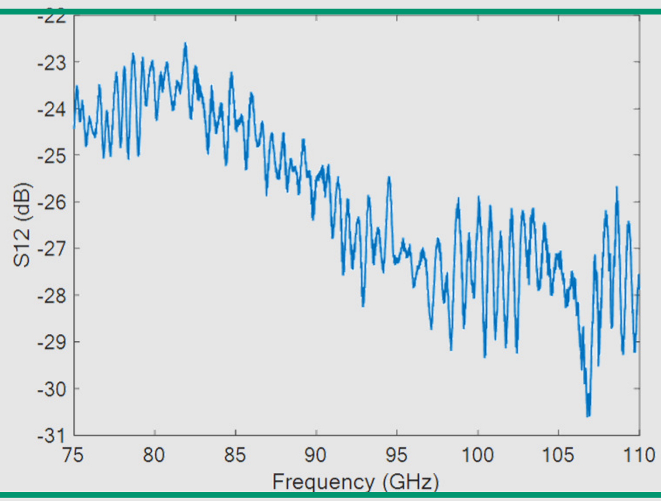
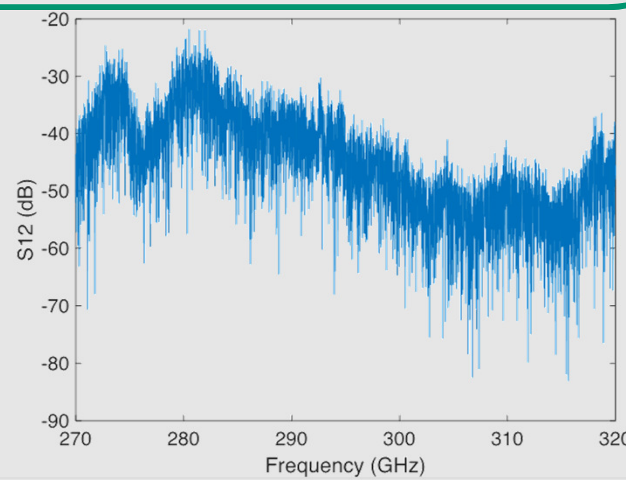
Communication methods



- Channel modelling

- Test-bed for the demonstration of >10 Gbps wireless communications
- Several stand-alone prototype nodes at around 90 GHz and 300 GHz

Measurement results: small office

	90 GHz band	300 GHz
Spatial Characteristics		
Transfer Function		

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Project Summary

iBROW will achieve a novel RTD device technology:

- On a III-V on Si platform
- Operating at mm-wave and THz frequencies
- Integrated with laser diodes and photo-detectors

A simple technology that can be integrated into both ends of a wireless link

- Consumer portable devices
- Fibre-optic supported base-stations.

Conclusion

- RTD oscillators up to 300 GHz with >1 mW output power demonstrated
- Opto-RTD oscillators with record output power of >10 mW at X-band demonstrated
- III-V (RTD) on Si approaches
- Low-cost high bandwidth THz transceiver technology