School of Electrical and Electronic Engineering
FACULTY OF ENGINEERING
UNIVERSITY OF LEEDS

THz quantum-cascade laser systems for atmospheric research & imaging

NASA image

Alexander Valavanis

a.valavanis@leeds.ac.uk

Overview

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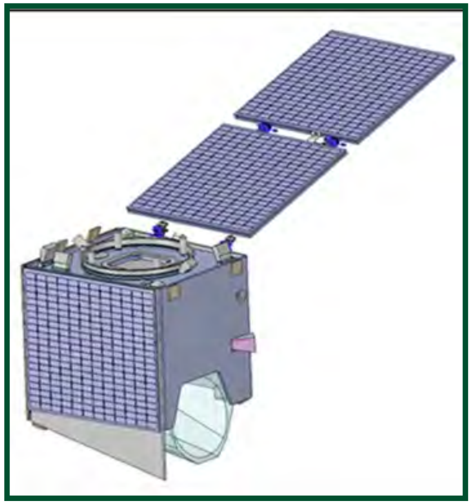
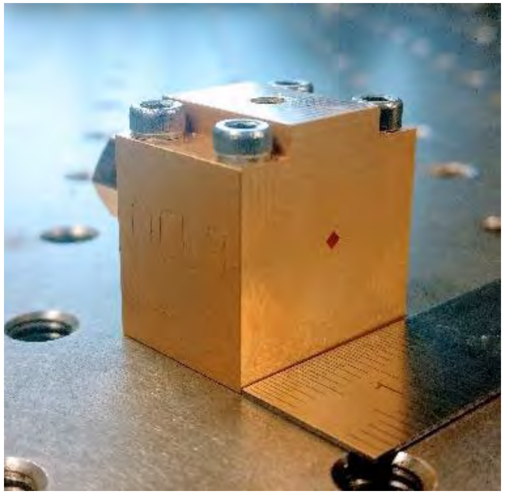
- Terahertz (THz) atmospheric & space research
- Waveguide integrated THz QCL systems
- Gas spectroscopy and imaging using THz self-mixing





Terahertz (THz) radiation

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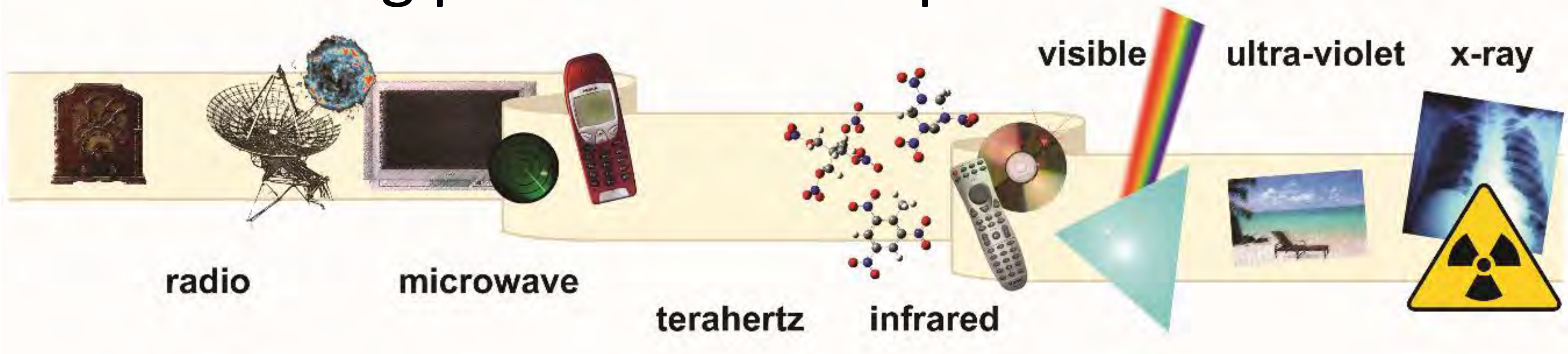
The meeting point between optics and electronics



Terahertz (THz) radiation

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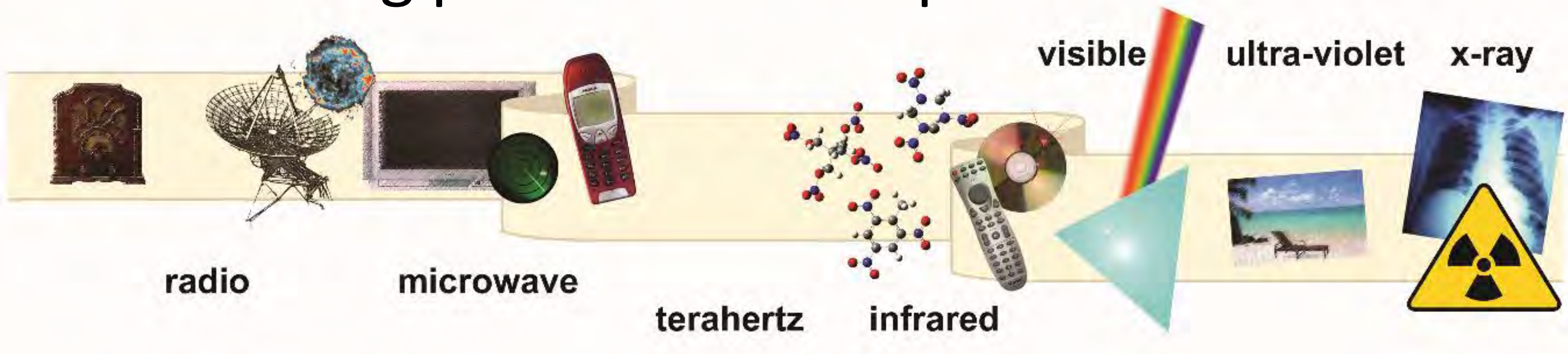
The meeting point between optics and electronics



Electronic oscillators

Terahertz (THz) radiation

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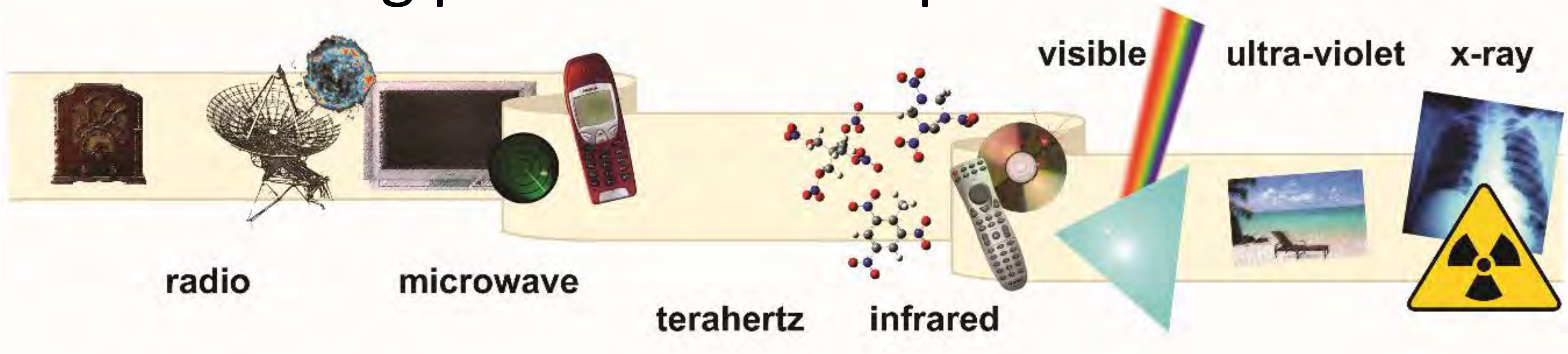
The meeting point between optics and electronics

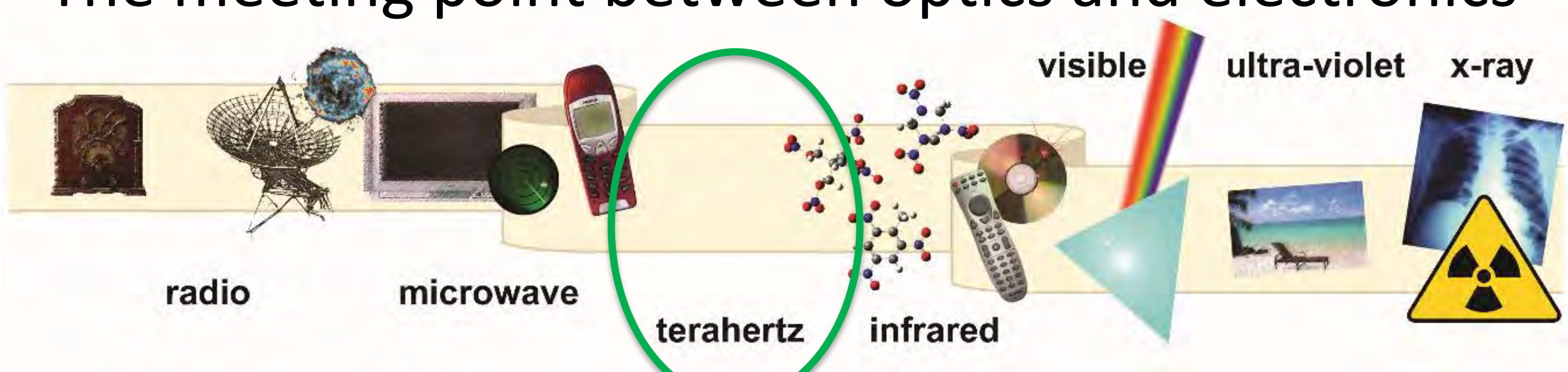


Electronic oscillators

Optical sources
(lasers, LEDs etc.)

Terahertz (THz) radiation

The meeting point between optics and electronics



Electronic oscillators

Optical sources

f = 0.3–10 THz λ = 1–0.03 mm

k = 10–333 cm^{-1} E = 1.2–40 meV

Properties and applications of THz waves

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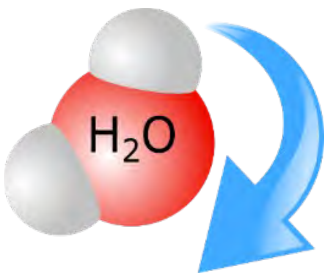
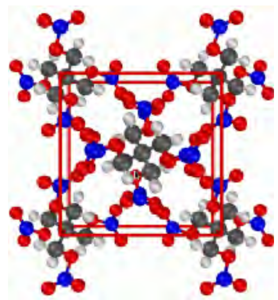
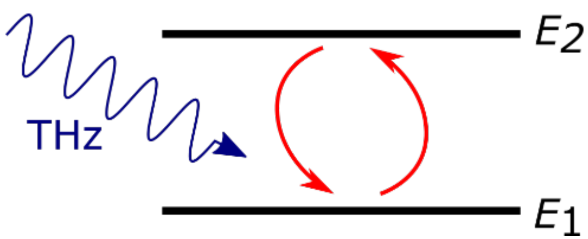
THz radiation highly sensitive to:



Rotational modes of gas molecules



Long-range order in crystals



Quantum states in semiconductors /superconductors

Security and industrial inspection	Condensed-matter physics	Atmospheric & space science	Bio-medical and pharmaceutical	Quantum technologies & quantum optics

THz gas spectroscopy

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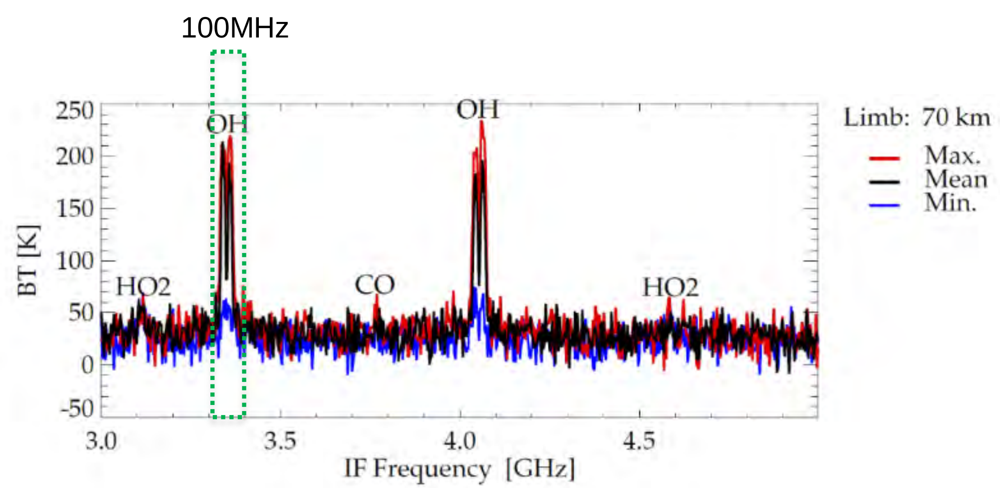
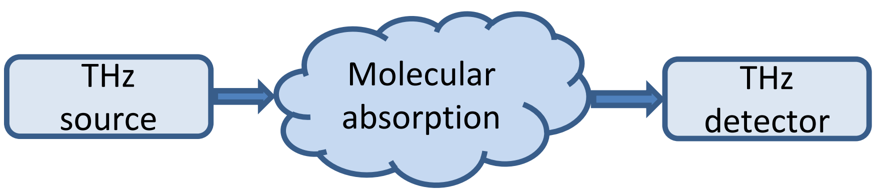
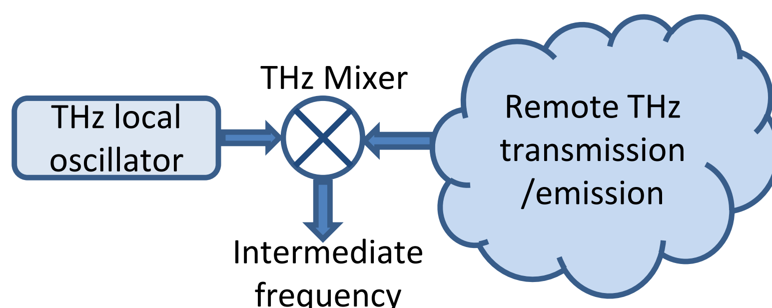
Spectral modes of several important atmospheric gases lie in THz band



Active sensing



Radiometry



THz radiation sources

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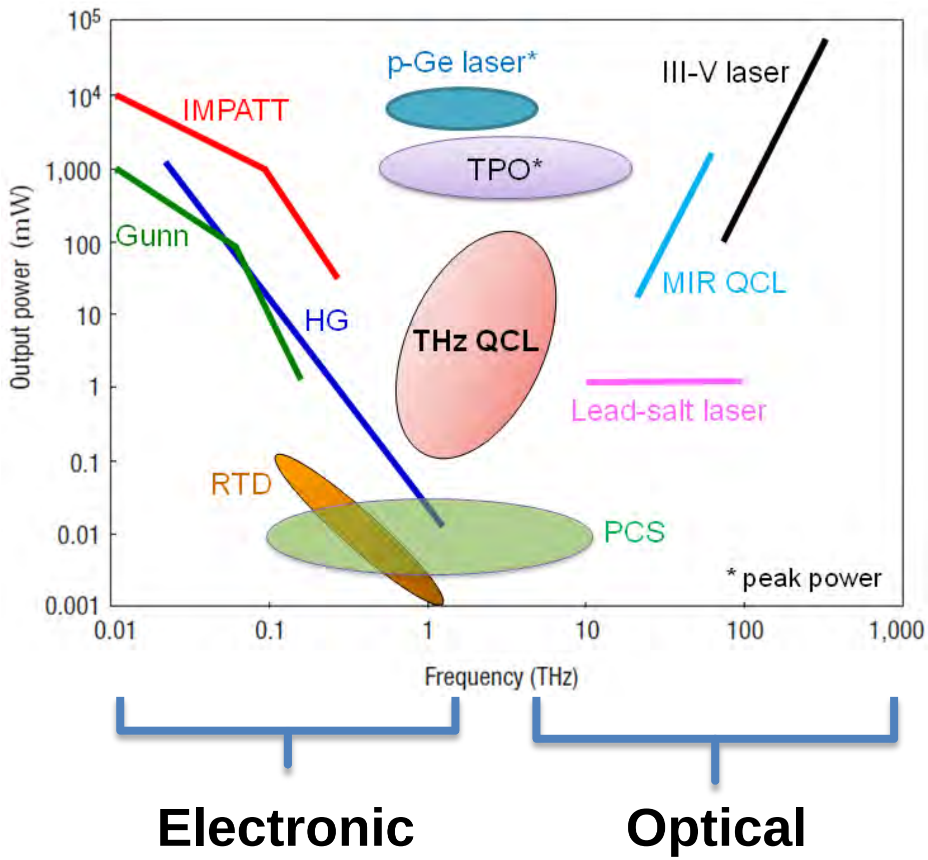

*Quantum-cascade lasers are the **only** compact & powerful THz sources*

IMPATT – Impact Ionization Avalanche Transit-Time diode
HG – Harmonic Generation
RTD – Resonant-Tunnelling Diode
TPO – THz Parametric Oscillator
PCS – Photoconductive Switch
QCL – Quantum Cascade Laser

M. Tonouchi, *Nature Photonics*, **1**, 97 (2007)

THz quantum-cascade lasers

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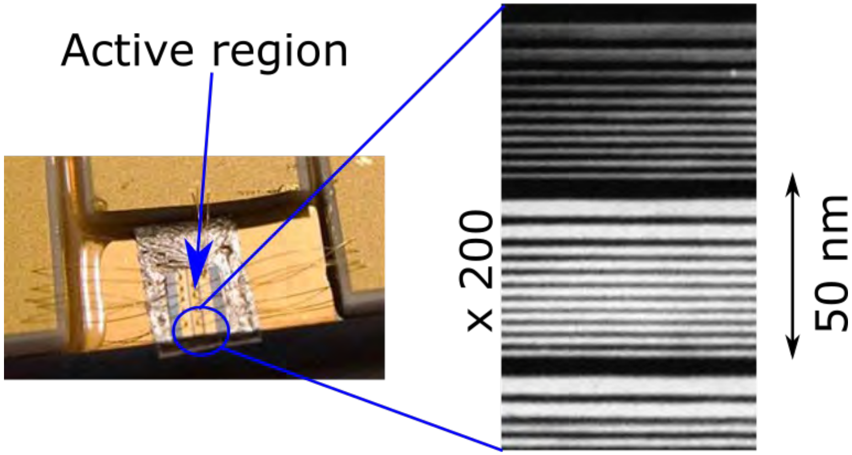
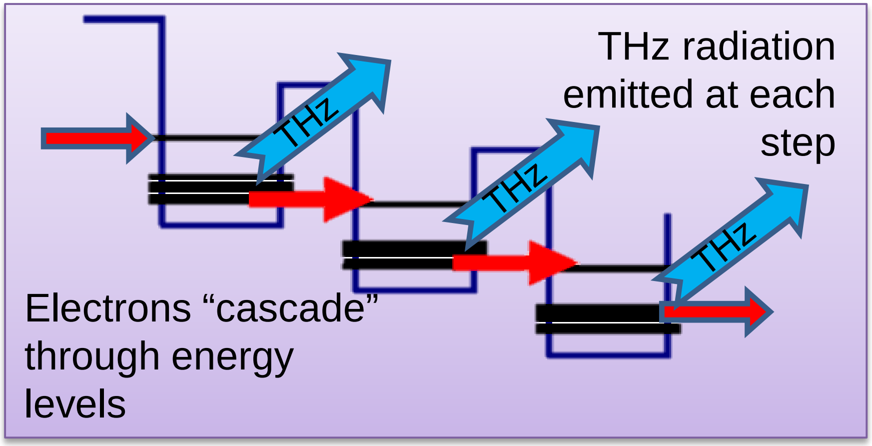
Epitaxially-grown GaAs/AlGaAs heterostructures within plasmonic waveguides





"Electron-recycling" process yields > 1 mW continuous-wave power in ~2-5 THz band

Integrated THz systems for space applications

The LOCUS Satellite concept

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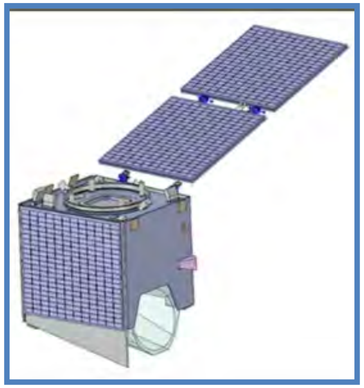
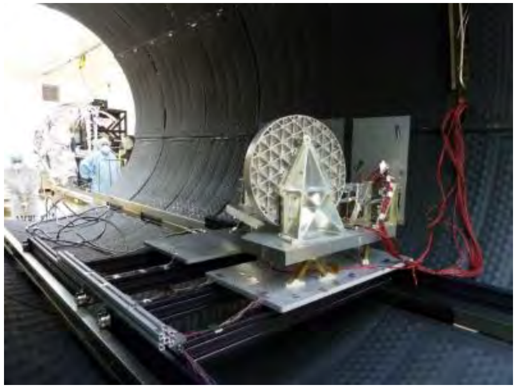
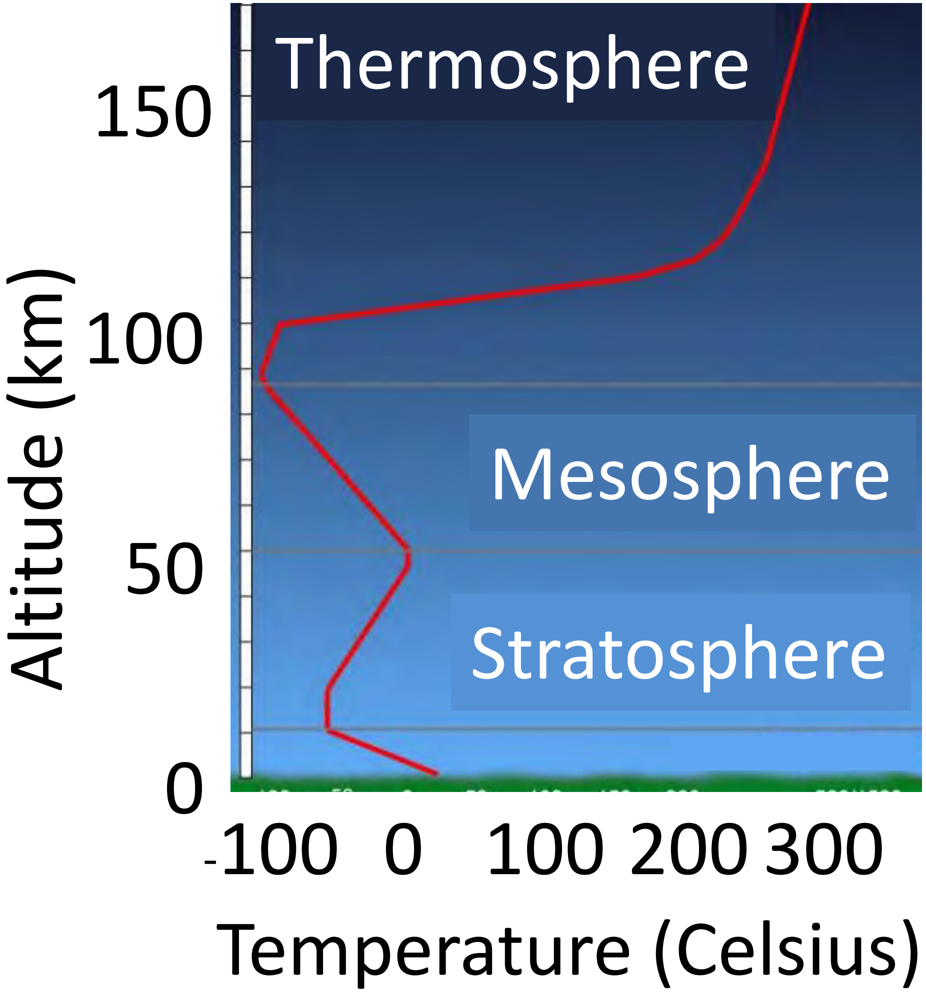
"Linking observations of climate, the upper atmosphere and space weather"







Supra-THz from Space

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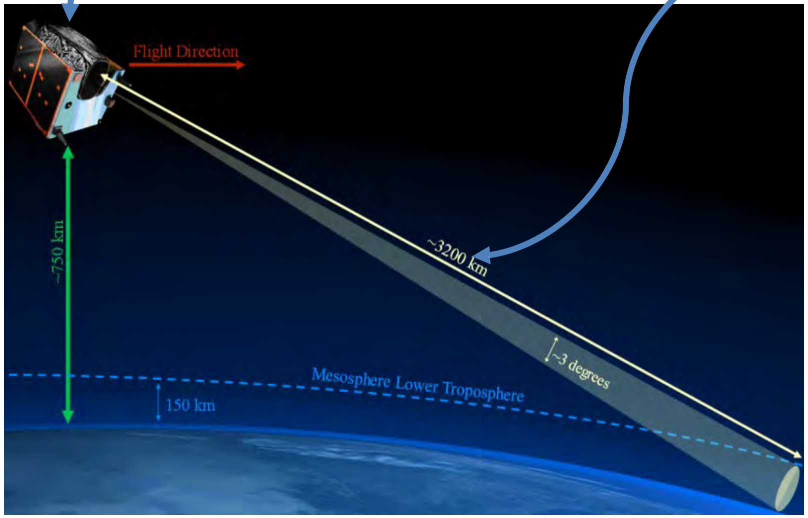
LOCUS Platform

Radiometer sampling beam



Global mapping of the Mesosphere & Lower Thermosphere, using THz receivers in low-Earth orbit

QCLs!

Designation	Band Centre	Primary Species	Secondary Species
Band 1	4.7 THz	O	O_3
Band 2	3.5 THz	OH	CO, HO_2
Band 3	1.1 THz	NO, CO	H_2O, O_3
Band 4	0.8 THz	O_2	O_3

LOCUS System Concept

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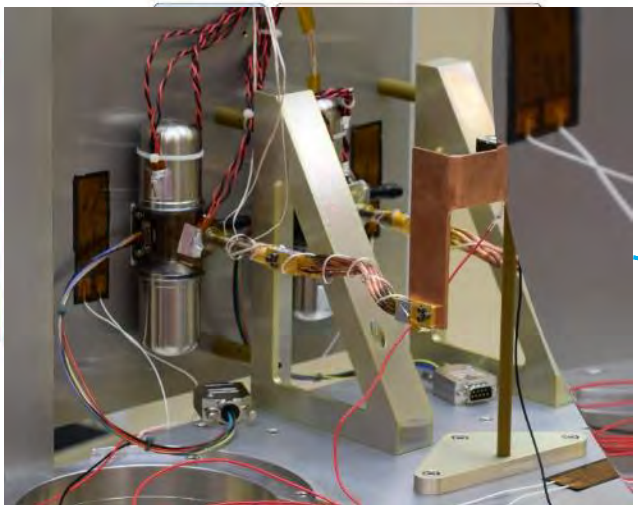
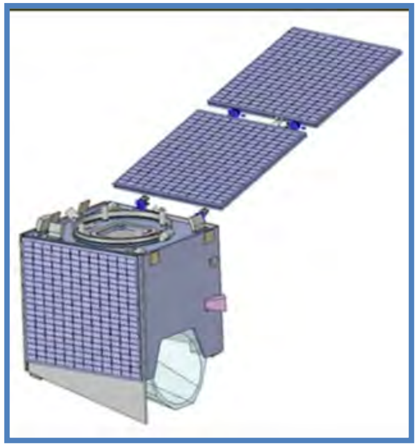
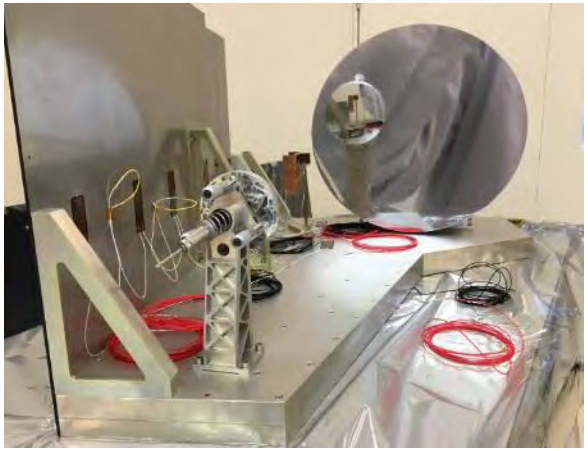
QCLs, Schottky diode mixers & Sterling cooler on a small satellite platform

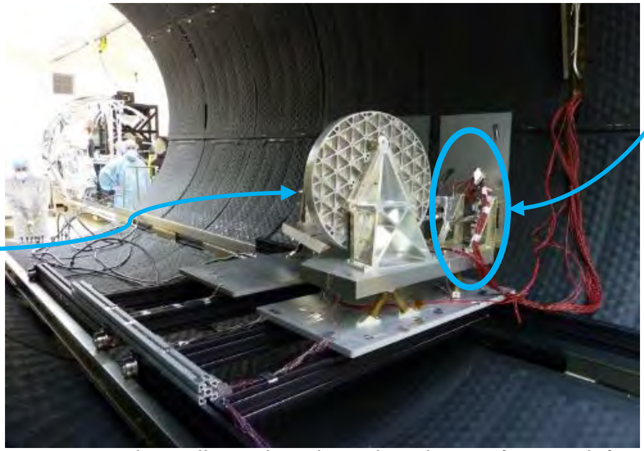


Miniature RAL cooler – courtesy Martin Crook, RAL Technology Dept.

LOCUS optical train – primary and secondary







LOCUS breadboard undergoing thermal vac. trial

LOCUS small satellite platform concept

LOCUS Core Technology

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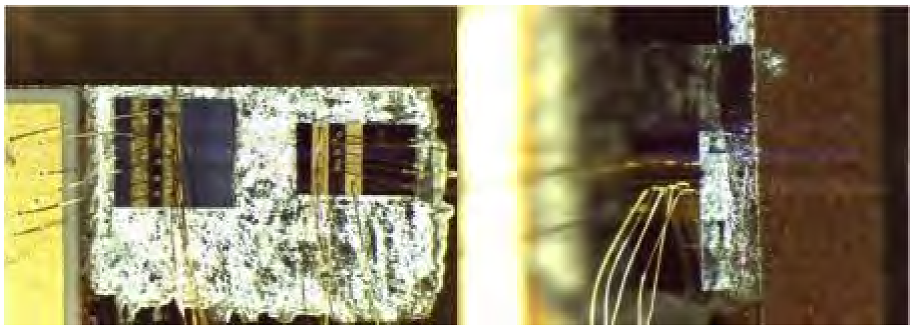
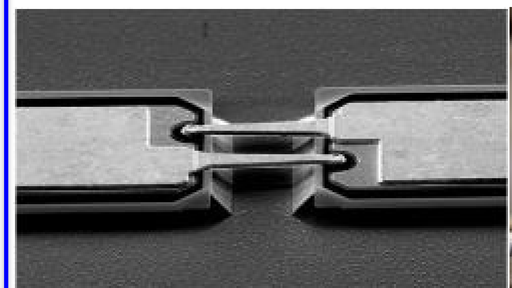
3.5 & 4.7 THz QCL
Local Oscillators
University of Leeds

Schottky Barrier Diode
& Space Coolers RAL





Digital Spectrometer
STAR-Dundee

UK also leading LOCUS science definition via
Leeds, UCL and RAL

Small Satellite
Surrey Satellites Ltd

LOCUS integration design

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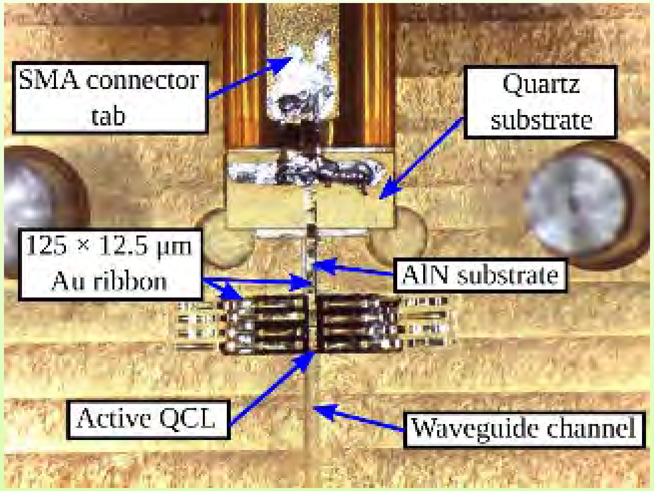
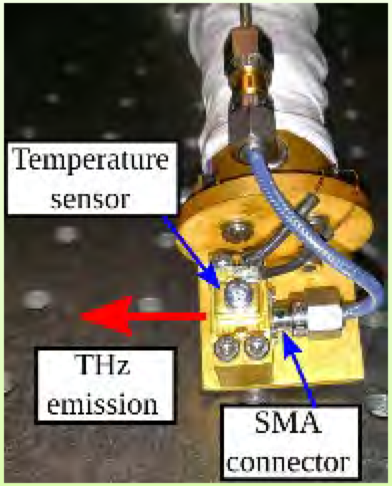
3.5-THz QCL integrated within precision micromachined waveguide





Valavanis et al., *Electron. Lett.* **51**, 919 (2015)

Dual-feedhorn design

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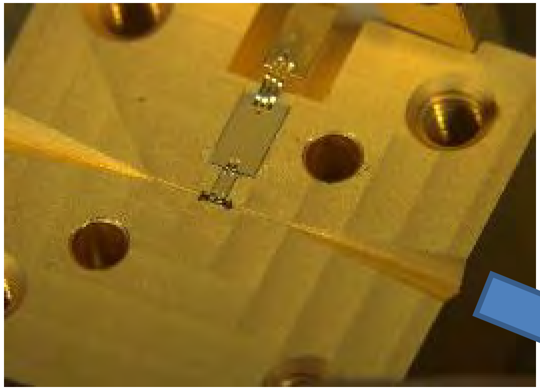
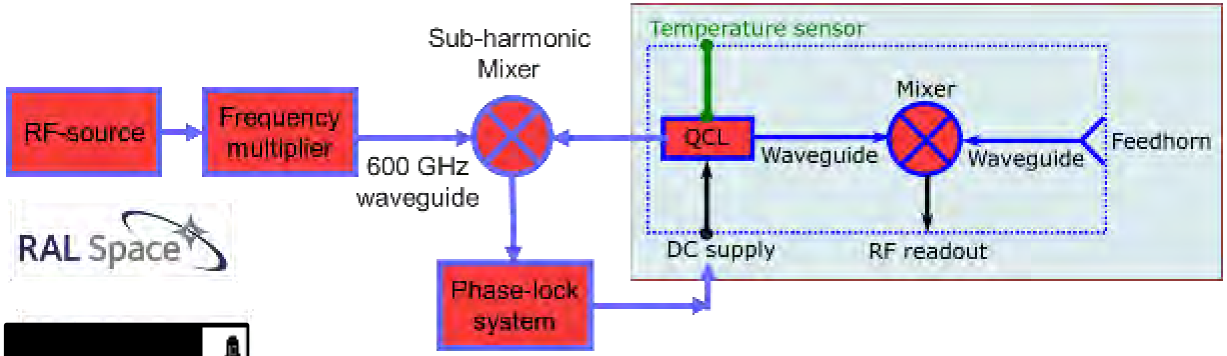
*Dual-feedhorn design enables simultaneous access to **both facets** of QCL*

Stabilisation subsystem



THz mixer



RAL Space

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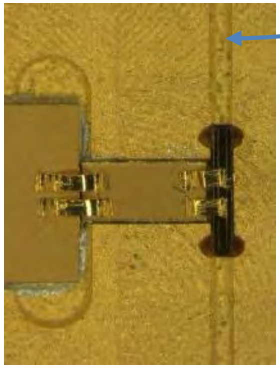
Waveguide 0.16x0.08mm^2



Cryocooler integration

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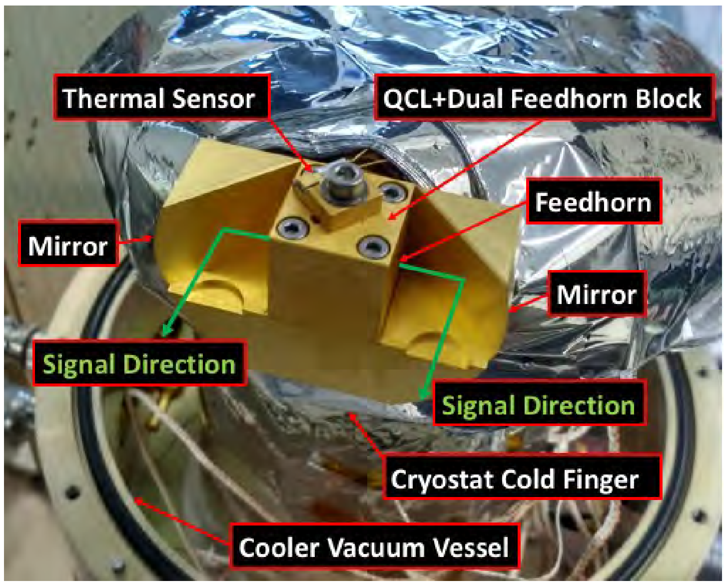

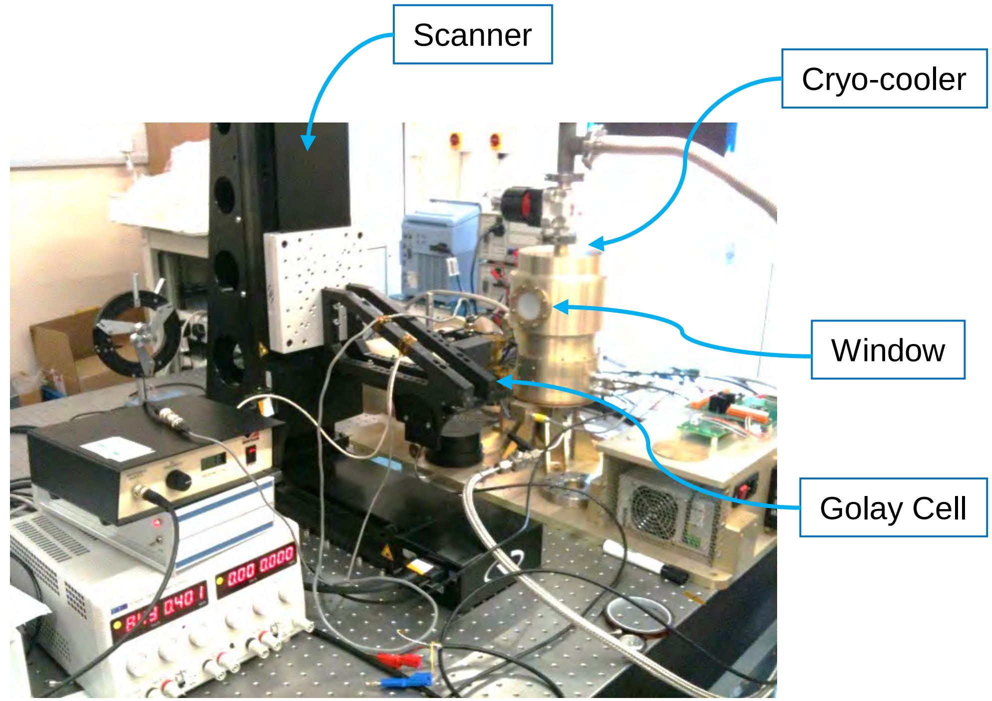

Operation within space-qualified Stirling cryocooler system

Beam-Pattern Measurement

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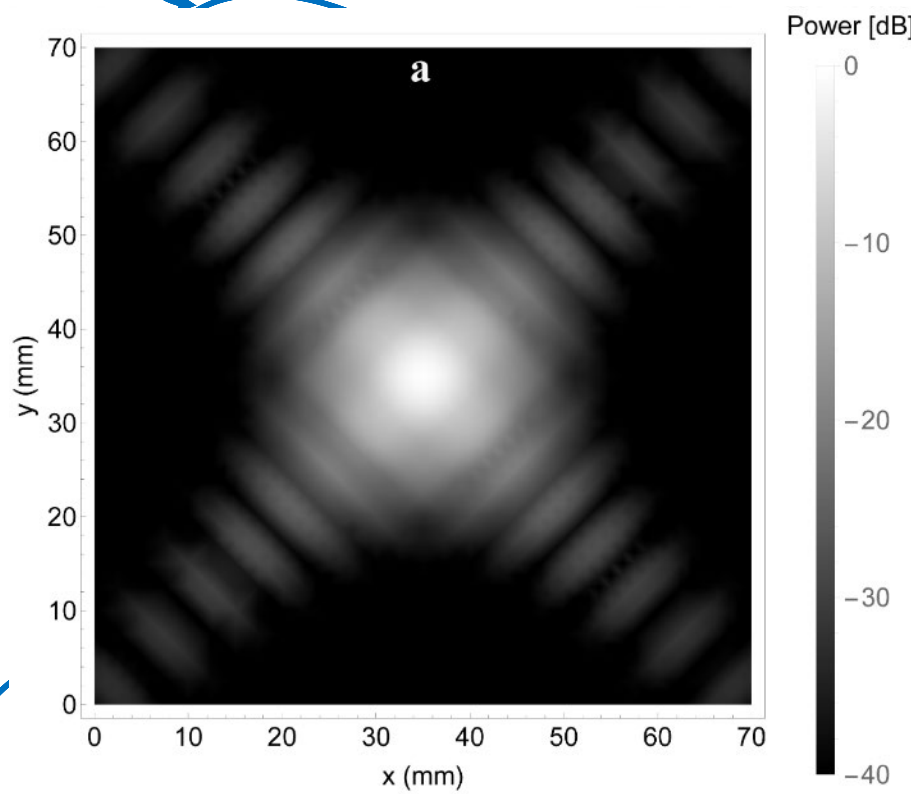
Beam-profiling using raster-scanned Golay detector

Sidelobe typical of diagonal feeds



Two central maxima corresponding to dual output of QCL

Imaging and spectroscopy using THz self-mixing

Self-mixing interferometry

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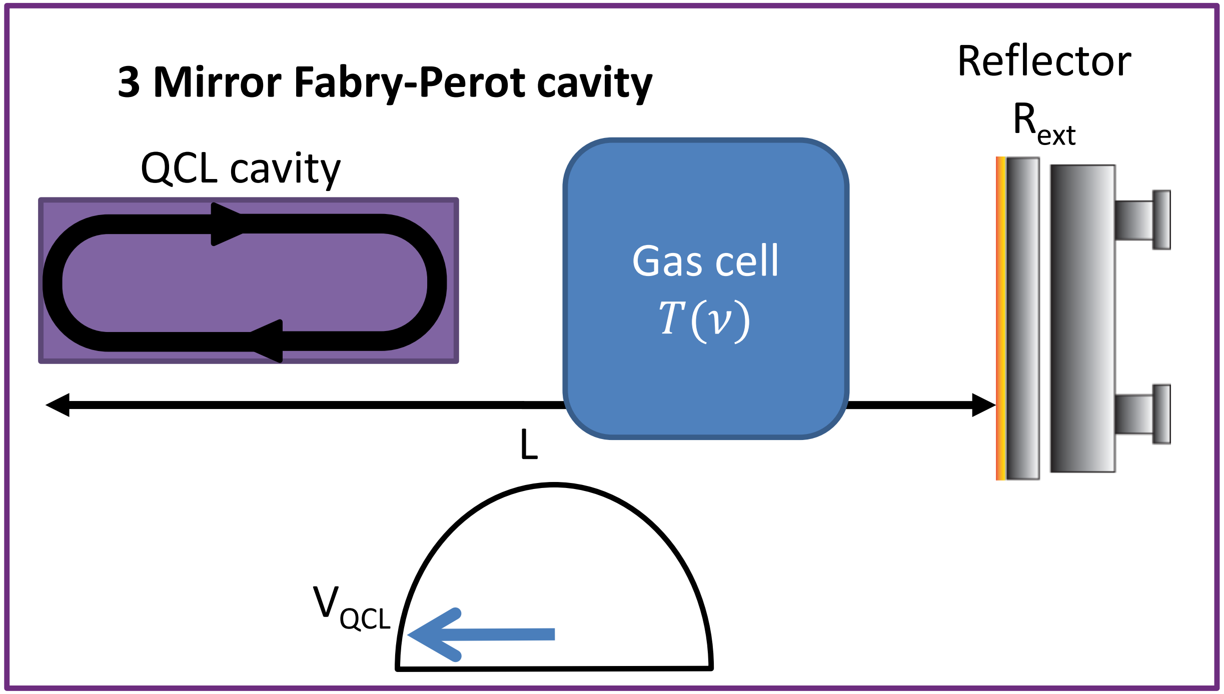
*THz **feedback** into a QCL perturbs the terminal voltage – **coherent detector-free sensing**!*



Self-mixing interferometry

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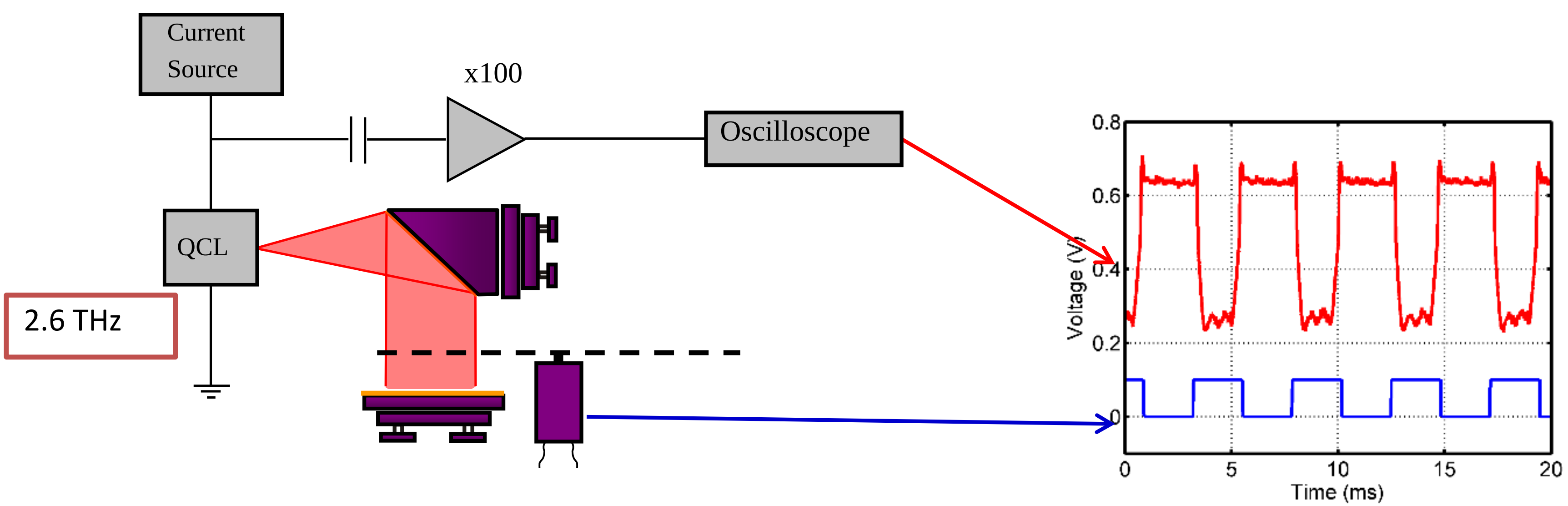
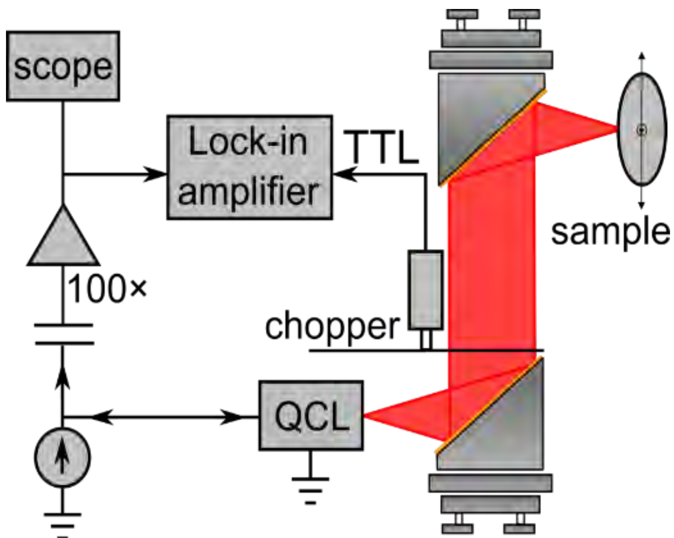
Change in external reflectivity (or cavity transmission) seen in QCL voltage



Opt. Lett. **36**, 2587-2589 (2011)

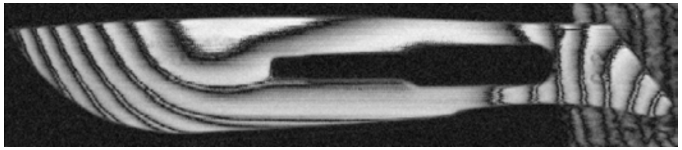
Confocal self-mixing imaging



THz-SM imaging gives λ ~ 100 μm resolution and provides surface-contour profiles

Imaging through packaging:

Imaging over >10 m stand-off:



A. Valavanis et al., IEEE Sensors J. **13**, 37 (2013); P. Dean *et al.*, Opt. Lett. **36**, 2587-2589 (2011),

Self-mixing interferometry

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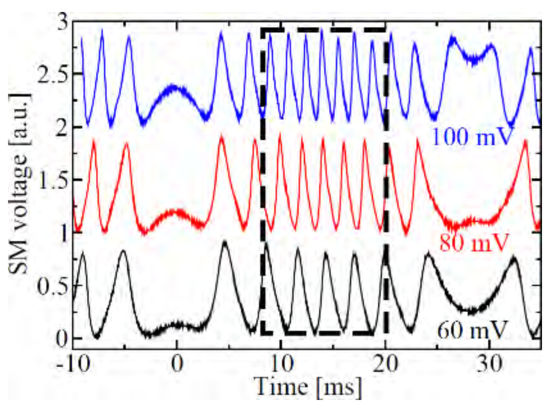
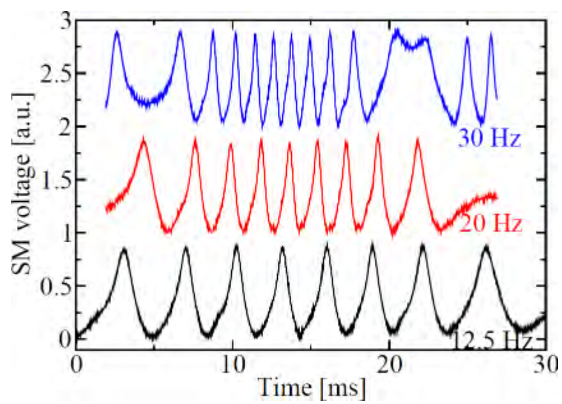
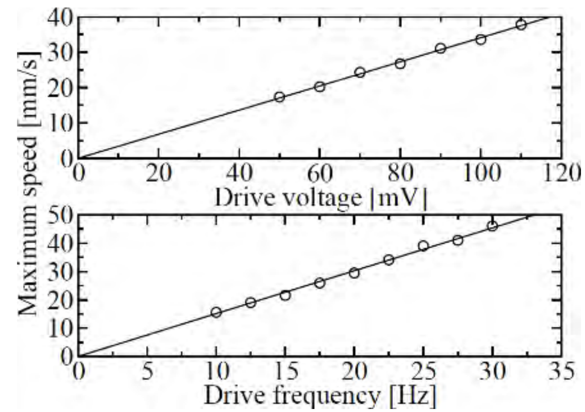
Can measure displacement (or velocity) of “hidden”, moving targets in real-time







Constant-velocity region

$V_{SM}(t)$ $\quad$ $v = \dfrac{f_0 \lambda}{2}$

A. Valavanis *et al.*, IEEE Sensors J. **13**, p.37 (2013)

3D surface profiling

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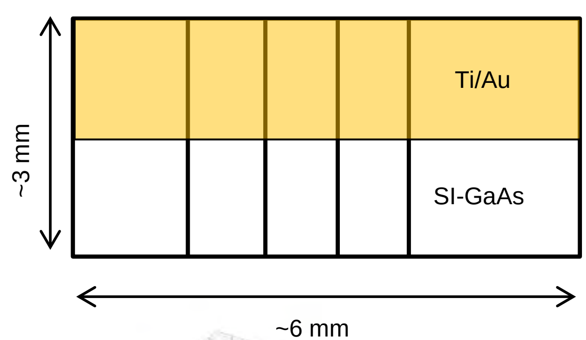
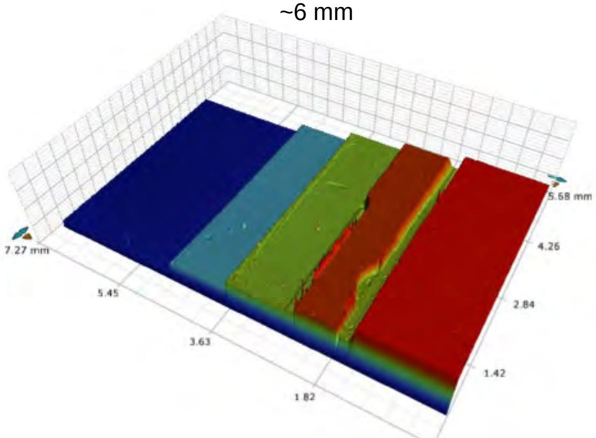
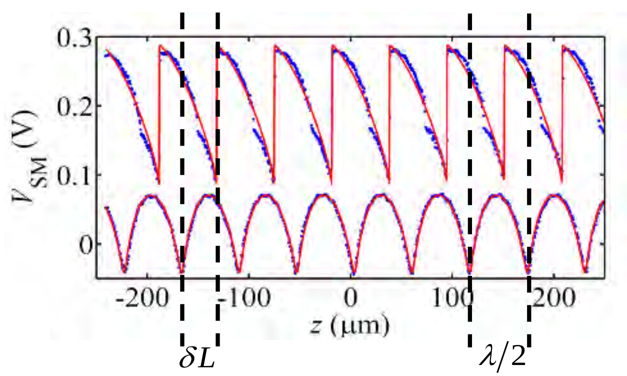
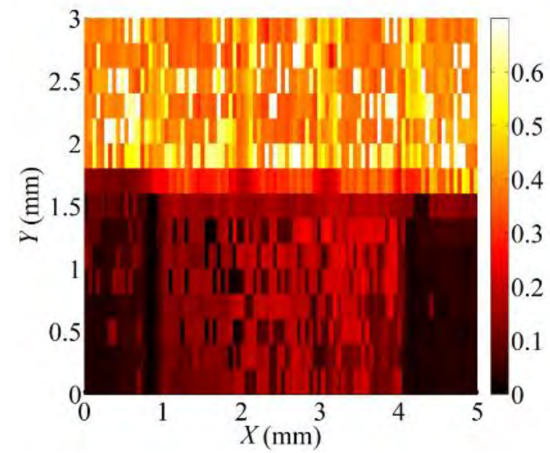
Reflectivity & surface profile can be extracted simultaneously from SM interferograms

Step height ~5 µm

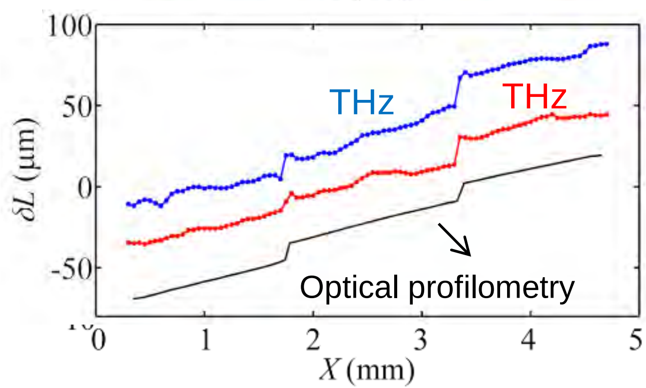




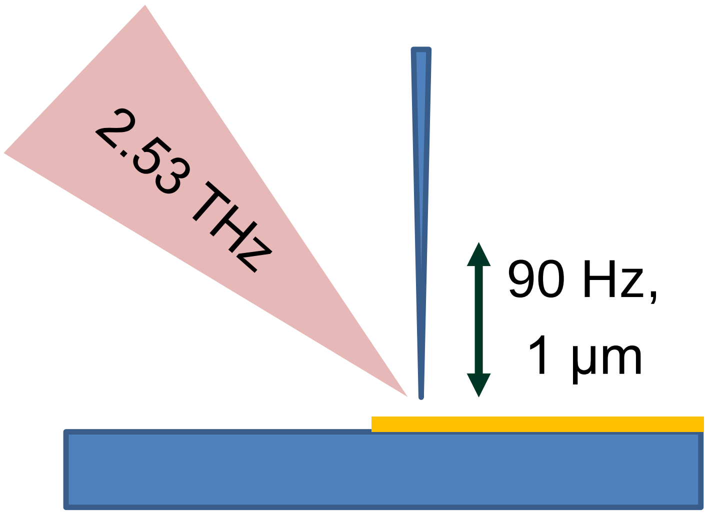


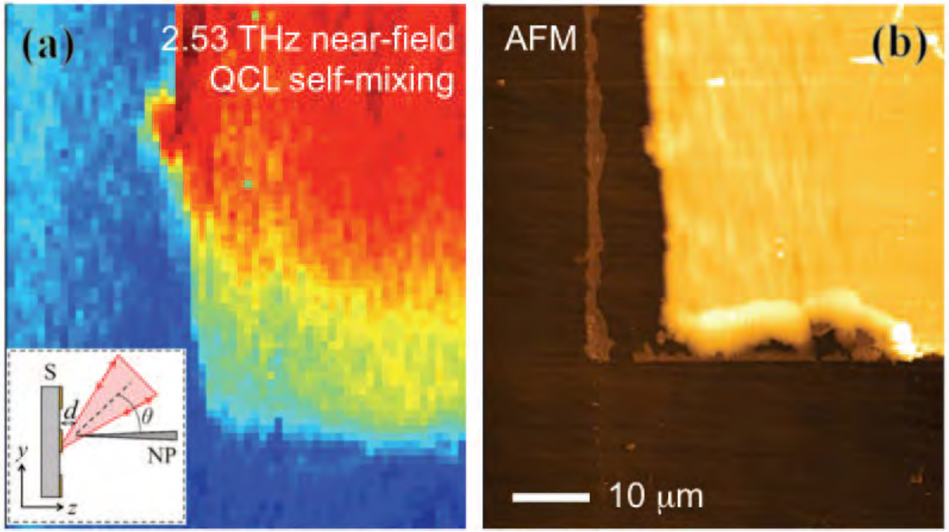


Appl. Phys. Lett. **103**, 181112 (2013),



THz near-field microscopy





Scattering from a ~1 µm tip induces a SM signal in a QCL.

Enables carrier-density mapping at microscopic scales ~λ/100.

P. Dean *et al*. IRMMW-THz, Paris (2019)

Self-mixing gas spectroscopy

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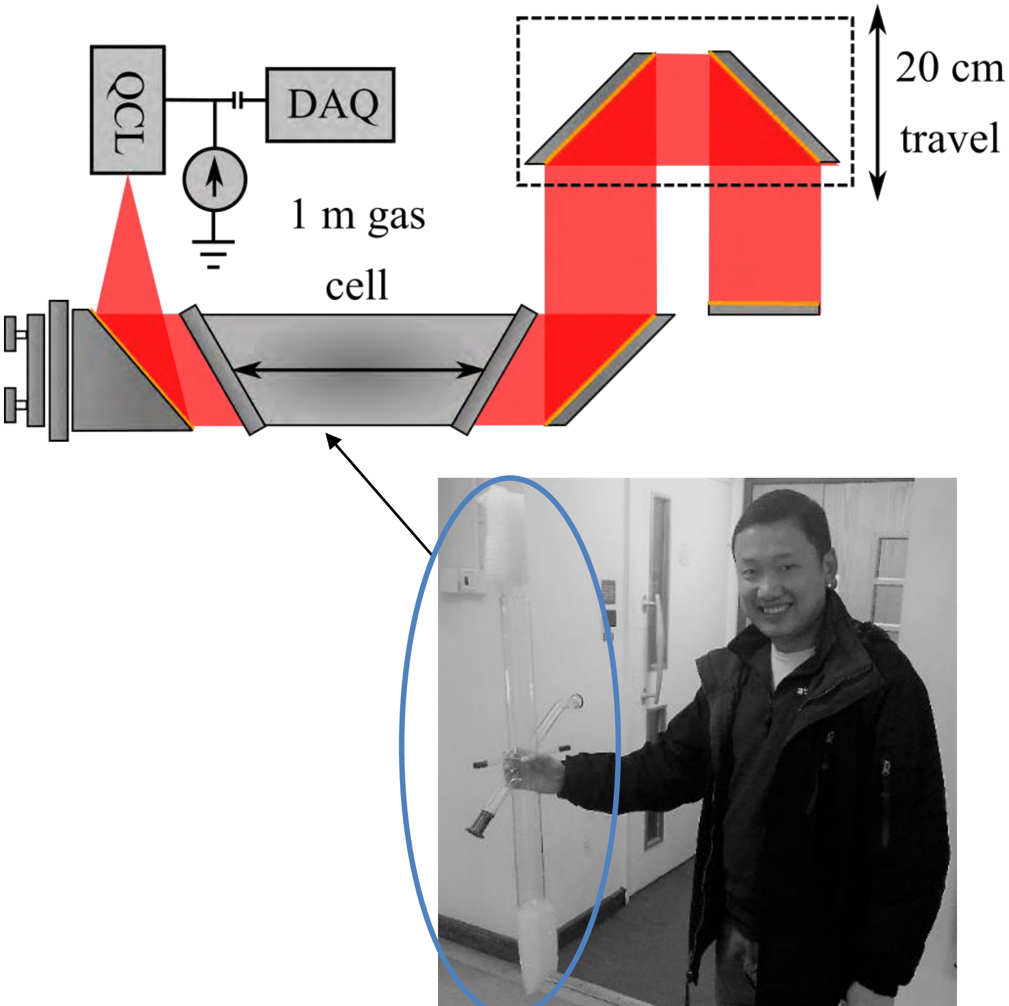

Adjust QCL frequency *by changing current and* ***measure transmission*** *through gas cell*

Multi-mode SM spectroscopy

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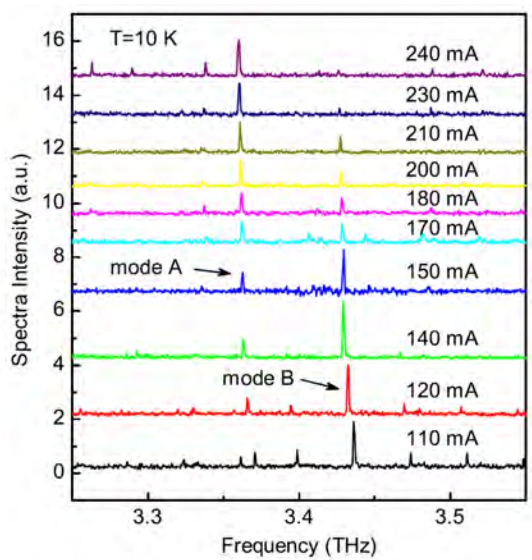
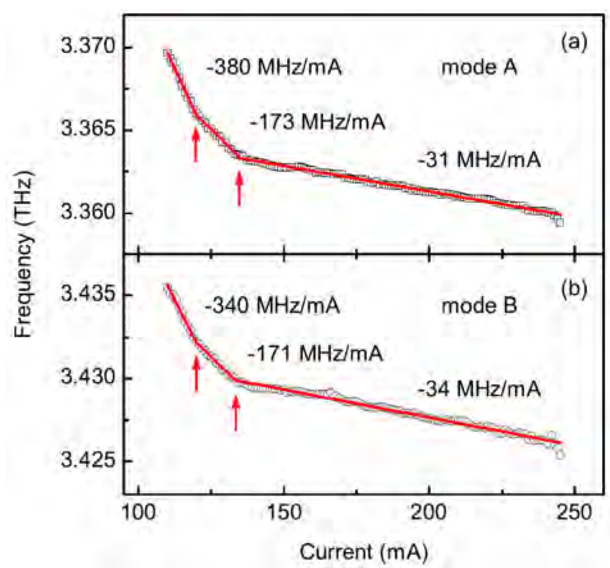
Multi-mode QCLs give huge spectral coverage (17-GHz) that cannot be achieved using simple power measurements

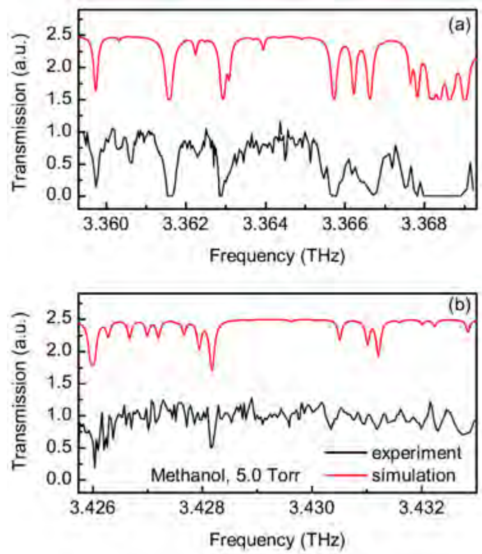
QCL emission



QCL tuning



Methanol spectra



Y. Han et al., *Opt. Lett.* **43**, p. 5933 (2018)

Summary

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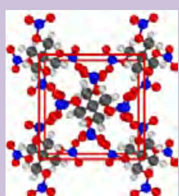
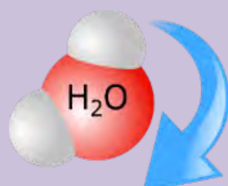
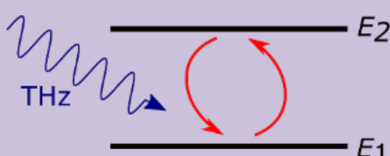
Unique sensing capabilities







Fully integrated THz systems

THz imaging and sensing

Postgraduate study opportunities available!

Acknowledgments

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- CEOI (7th, 8th and 10th call)
- UK Space Agency and ESA
- Royal Society & Wolfson foundation
- STFC Centre for Instrumentation
- UKRI Future Leaders Fellowship

Colleagues and collaborators

- Valavanis group: Y. Han, M. Horbury, E. Zafar, E. Nuttall, S. Kondawar
- Leeds THz lab (Dean, Freeman, Burnett, Keeley, Li, Salih, Davies, Cunningham, Linfield *et al*)
- RAL Space (Ellison, Pardo, Gerber)
- University of Queensland (Rakic, Lim, Taimre, Agnew, Han, Qi)