School of Electrical and Electronic Engineering
FACULTY OF ENGINEERING

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THz Quantum-Cascade Lasers for Heterodyne Techniques

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Overview

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- *LOCUS* "supra-terahertz" radiometry channels
- THz quantum-cascade lasers
- Waveguide integrated THz QCL systems

LOCUS – *Linking Observations of Climate, the Upper-atmosphere and Space-weather*

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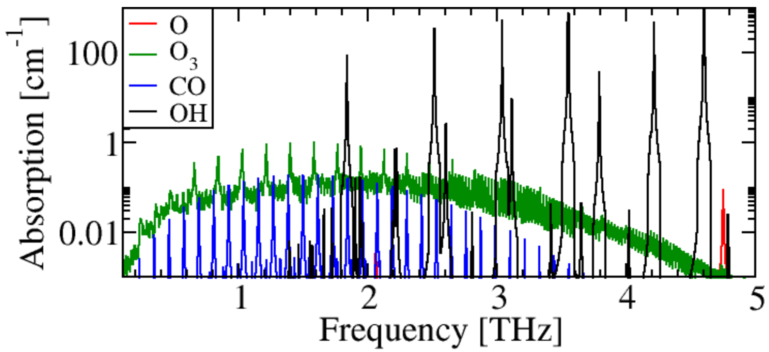
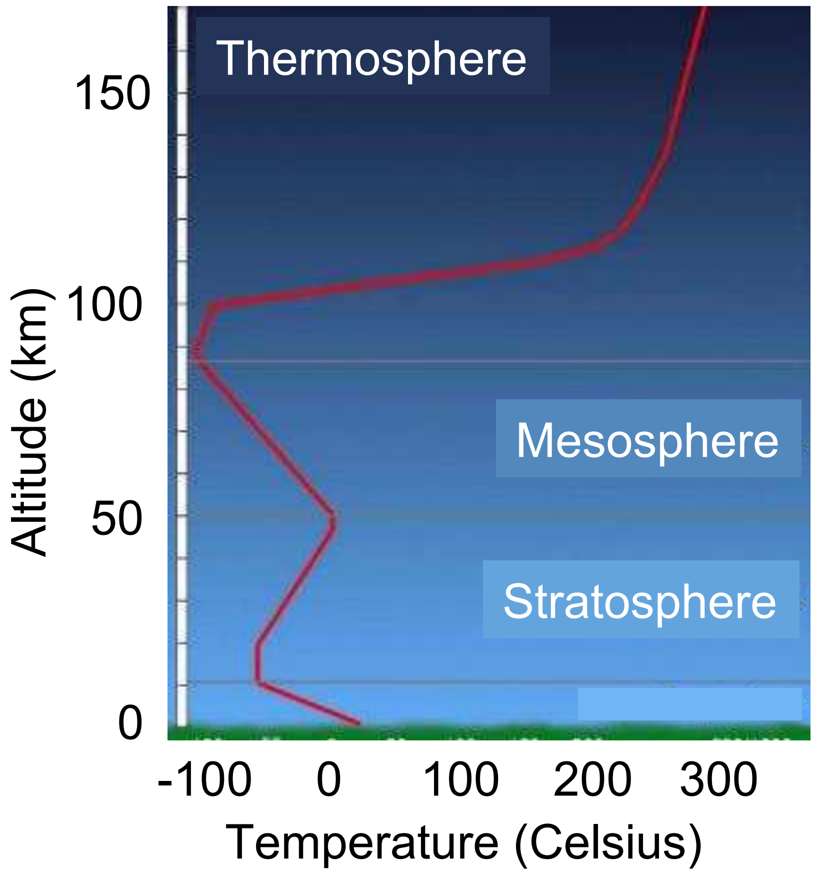
A breakthrough THz remote sounder
www.locussatellite.com

- Compact payload for small satellite
- Measure key species in mesosphere & lower thermosphere
- "Gateway" between Earth atmosphere & near-space
- Increase understanding of natural & anthropogenic effects on climate change





Integrated, compact and efficient source of THz radiation are needed

Radiometry system architecture

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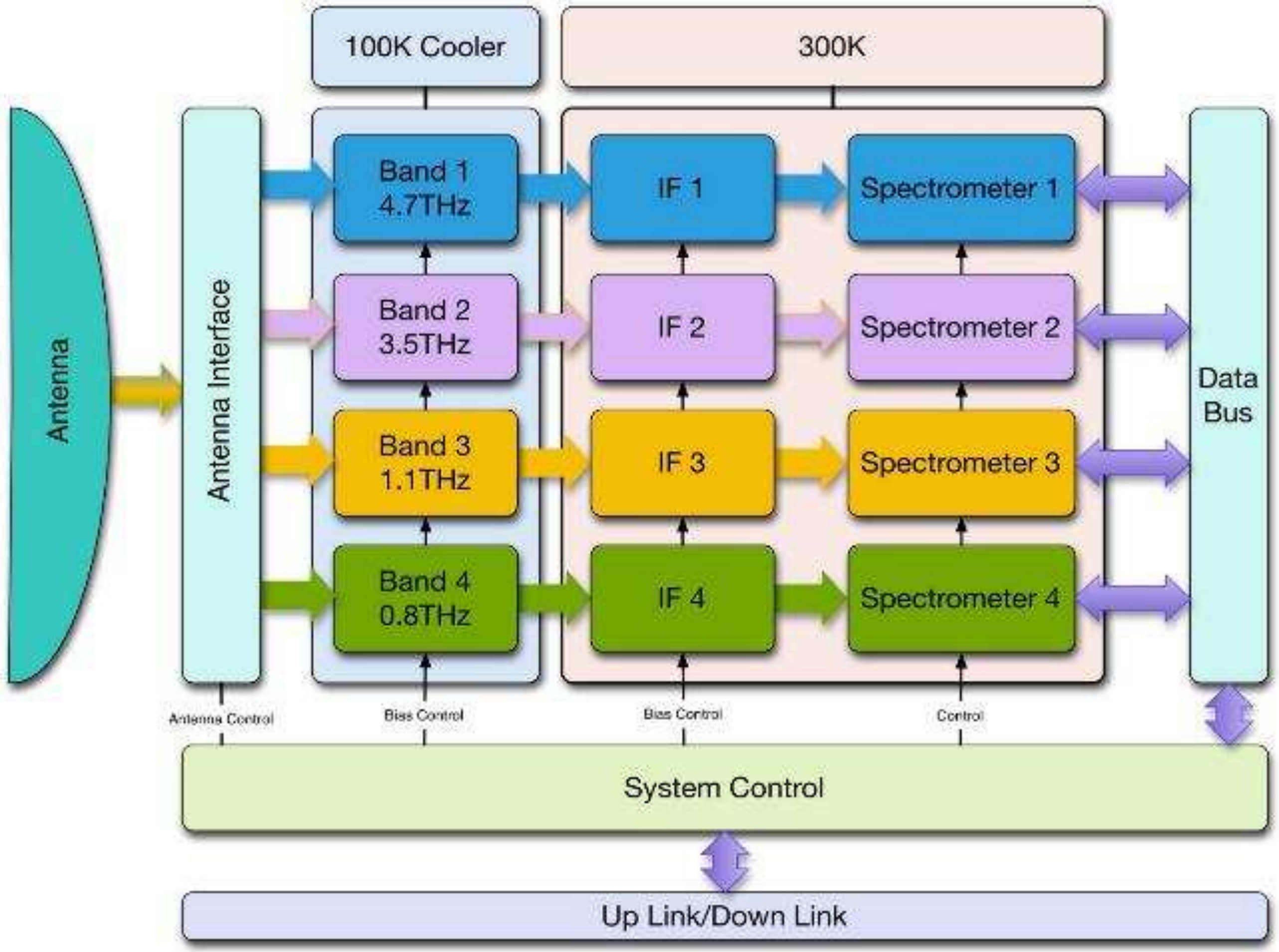

System schematic

THz LO requirements

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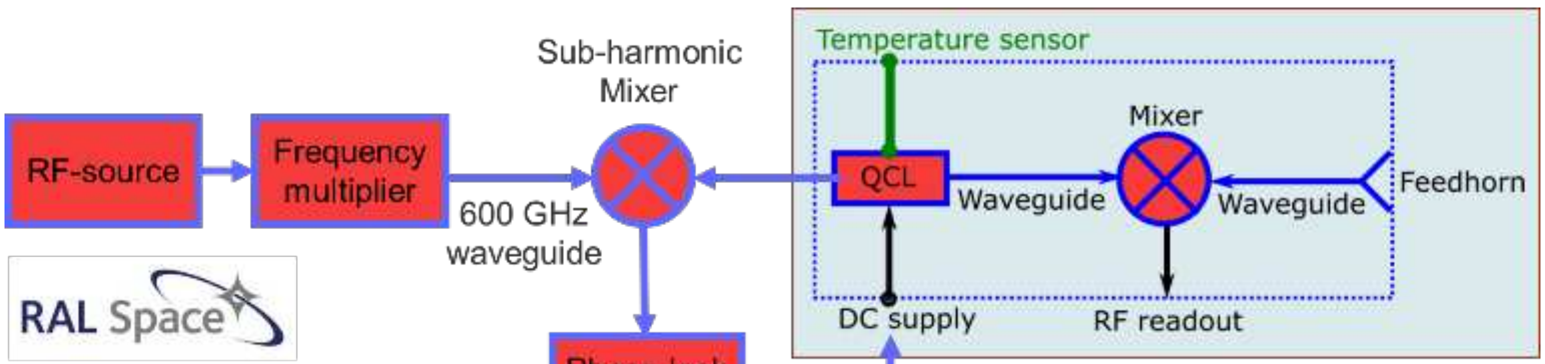
- 1 mW local-oscillator output power
- Compact, low-mass
- Low input power (< 5 W)
- Fully integrated within satellite-ready cryo-cooler
- 4 GHz tunability



Operating within satellite cryo-cooler

THz radiation sources

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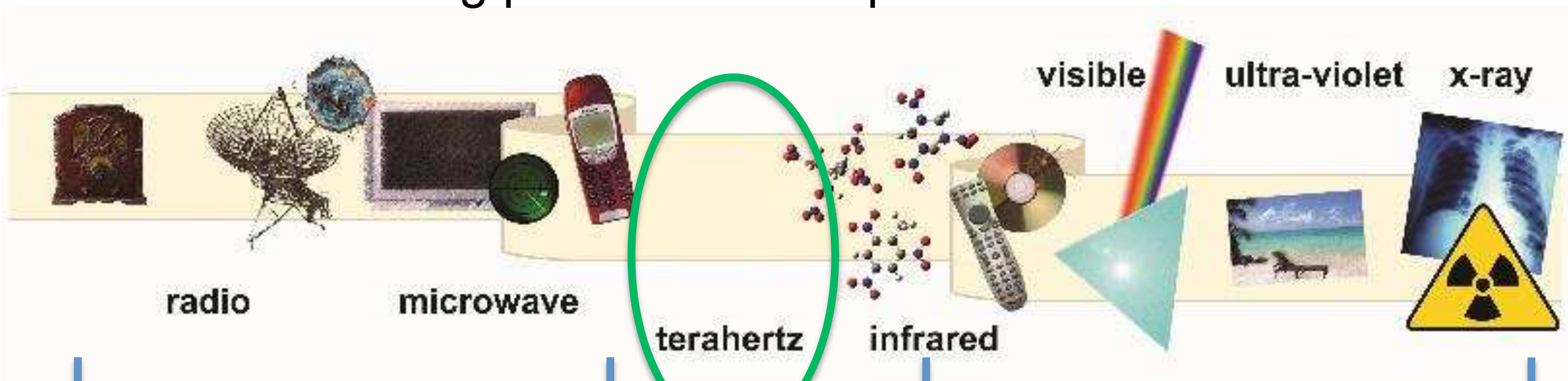
The meeting point between optics and electronics



Electronic (classical) oscillators

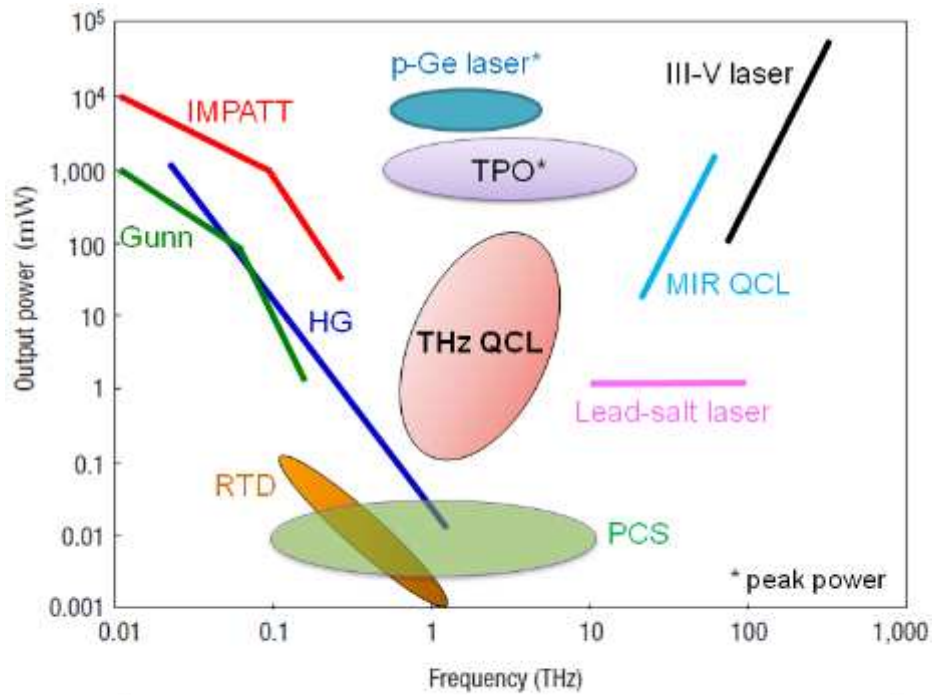
- Diodes / harmonic generators
- Limited to low frequencies by transit times

The "THz gap":
f = 2–10 THz

Optical (quantum) oscillators

- Lasers / LEDs / atomic transitions
- Limited to high frequencies by energy states in materials

THz radiation sources



Electronic **Optical**

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

THz Quantum cascade lasers (QCLs) are the only compact & high-powered coherent 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

THz semiconductor lasers

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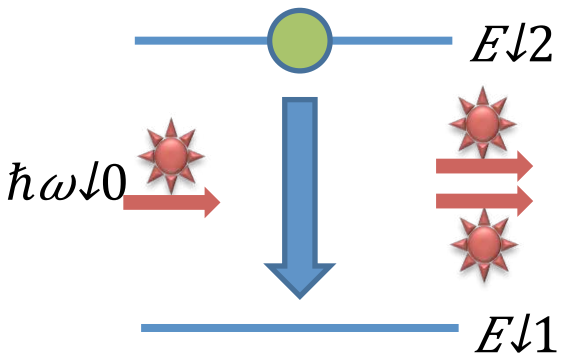
Semiconductor device requirements:

- Low enough energy level separation for THz photon emission
- More electrons at high energy than low energy (i.e., a population inversion)



$$h\nu = \hbar\omega_0 = E_2 - E_1$$

$$h = 4.14\times10^{-15}\ eV\,s$$
$$= 4.14\ \mathrm{meV\ /\ THz}$$

Absorption occurs: If particle is initially in low-energy state

Emission occurs: If particle is initially in high-energy state

Conventional laser diodes

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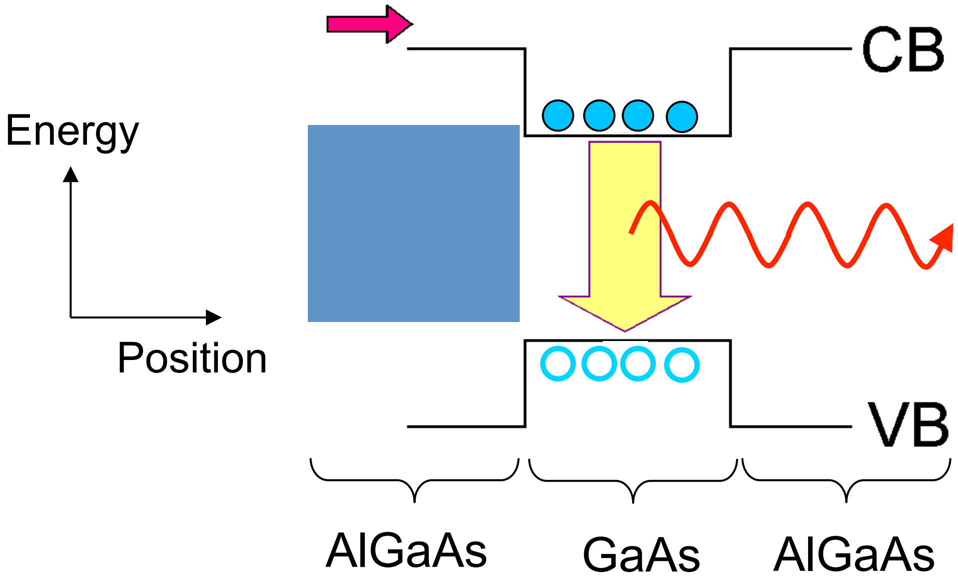


$$h\nu \geq E_c - E_v = E_g$$

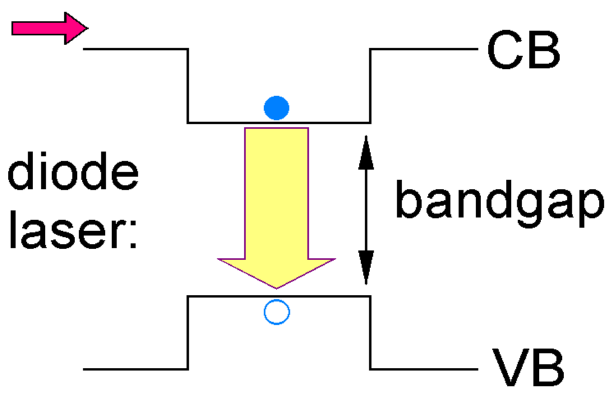
Both electrons and holes involved in (stimulated) emission of photons (bipolar device). One photon per electron (ideally).

Minimum photon energy = semiconductor bandgap

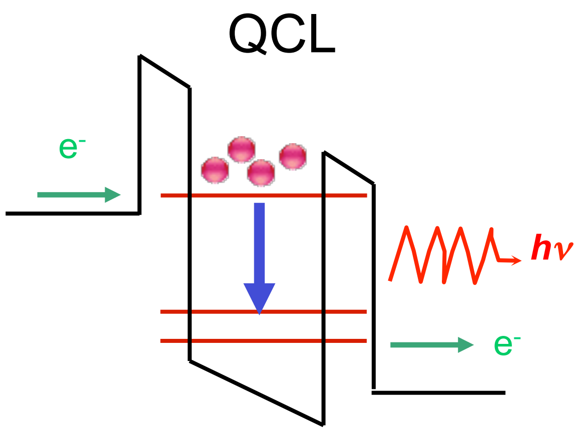
THz emission impossible with conventional bulk semiconductors

Quantum cascade lasers

The solution: use nanoscale layers. Quantum-confinement gives customisable band energies



$$\hbar\omega_0 \geq E_g$$



$$\hbar\omega_0 = \varepsilon_3 - \varepsilon_2$$

Intersubband transitions in quantum wells

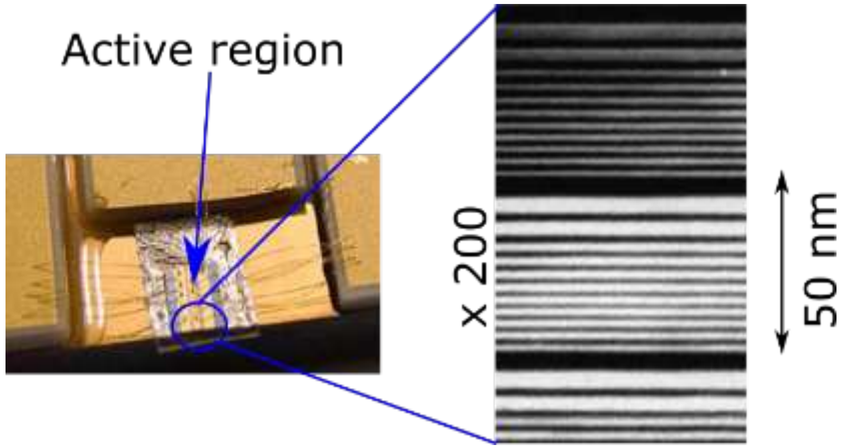
•Long-wavelength emission—Not bandgap limited

•Periodic system: electron 'recycling'

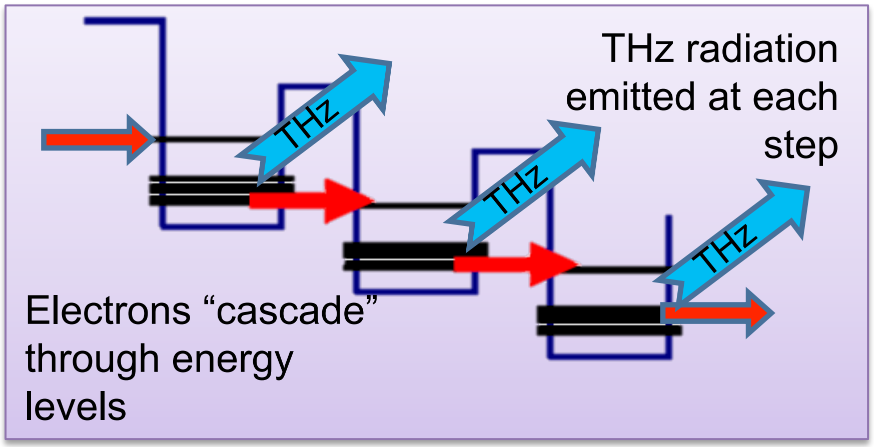
Quantum cascade lasers

The first powerful and compact continuous-wave THz source:

- ~1000 semiconductor layers, grown using molecular-beam epitaxy
- “Electron-recycling” → efficient THz generation
- 1 W pulsed THz power; ~100 mW continuous-wave
- 1–5 THz range



~1x10^5 magnification



Electronic behaviour

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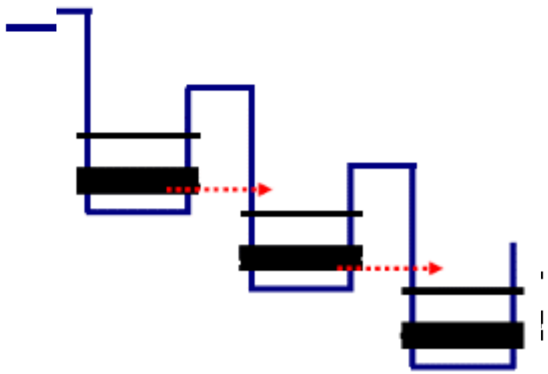
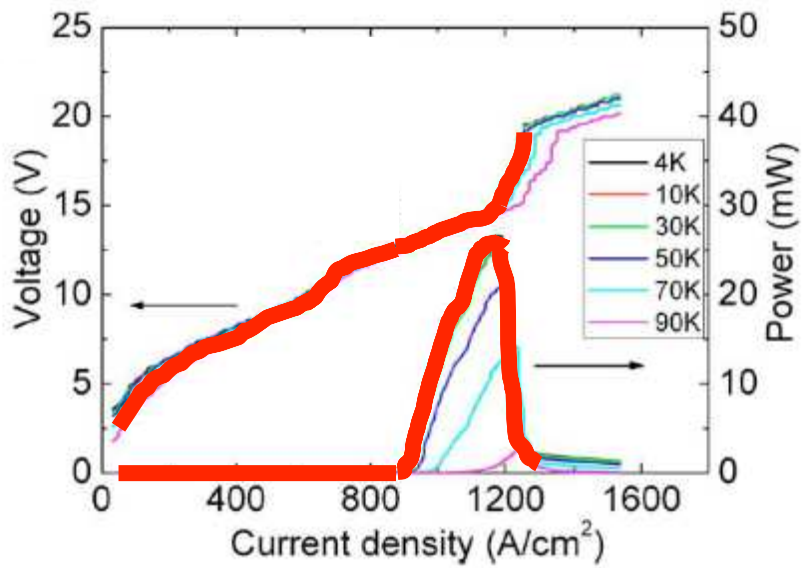
Peak THz power corresponds to efficient injection of current:

- Lower “upstream” energy bands align with upper “downstream” bands
- Population inversion yields THz gain





LOCUS Core Technology

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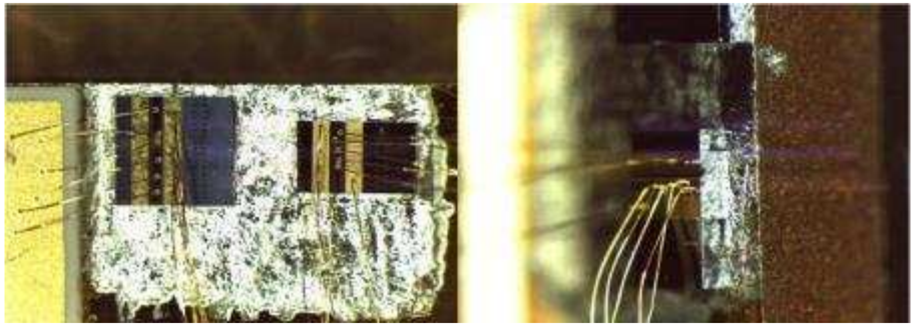
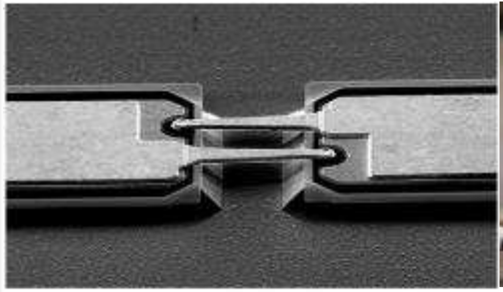
3.5 & 4.7 THz QCL
Local Oscillators
University of Leeds



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

Recent integration approaches

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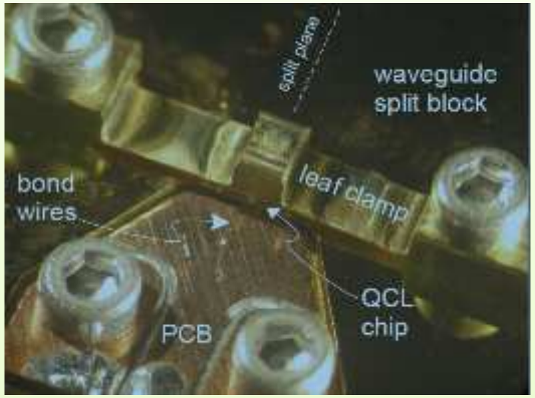
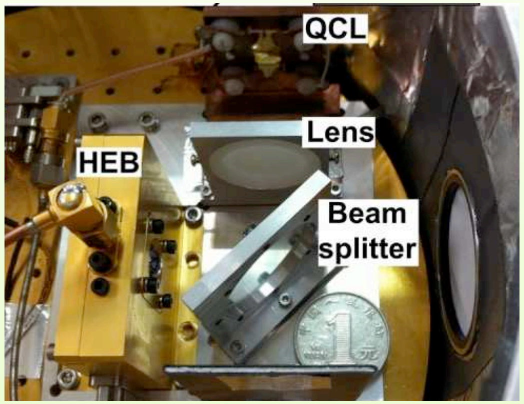


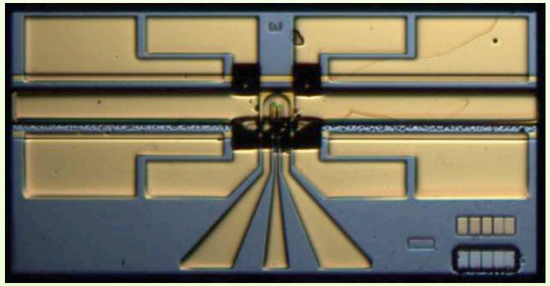
QCL
+ waveguide
+ horn antenna

Justen et al., 26th Int. Symp. Space THz Tech (2015)



QCL
+ HEB mixer

Miao et al., *Opt. Express* **23**, 4453 (2015)



QCL
+ Schottky mixer (monolithic)

Wanke et al., *Nat. Photon.* **4**, 565 (2010)

LOCUS integration design

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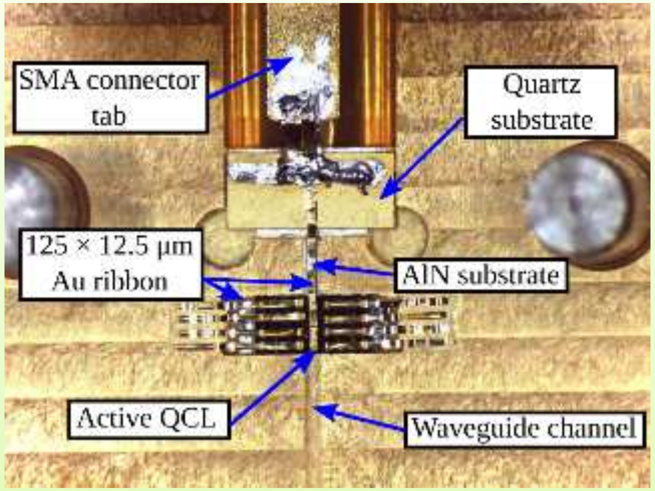
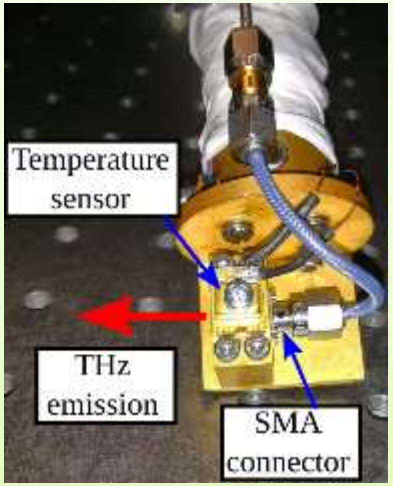
- Double metal 3.5 THz QCL
- Precision-micromachined 300 × 150 µm Cu waveguide
- High-frequency electronic ribbon-bonding + SMA
- Integrated temperature sensor





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

CW characterisation

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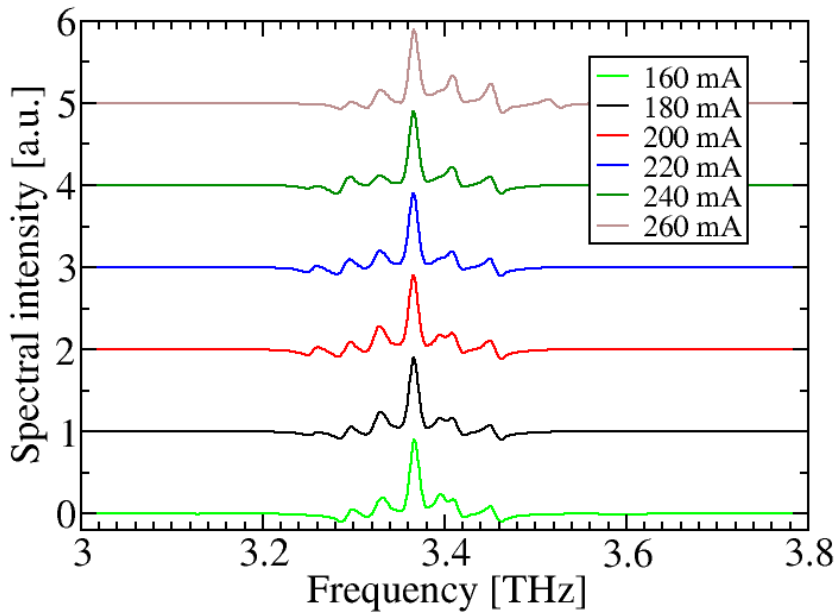

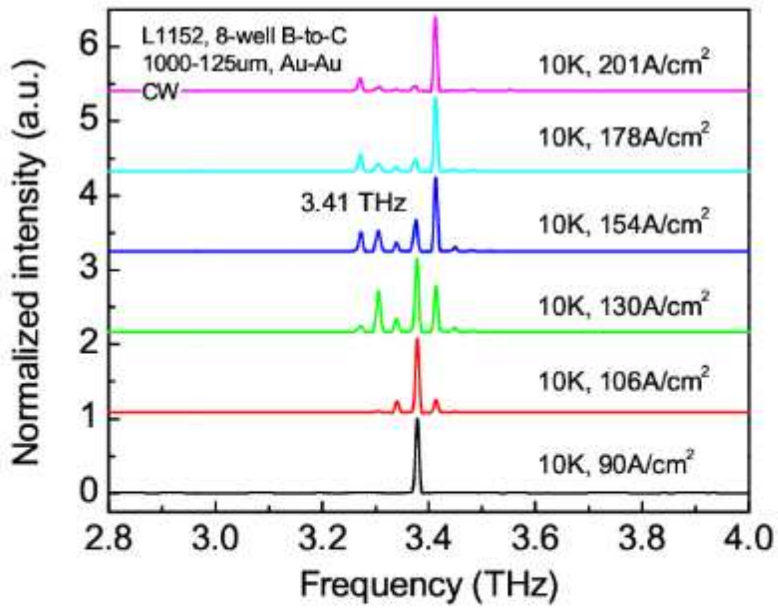

Mounted

Unmounted

CW characterisation

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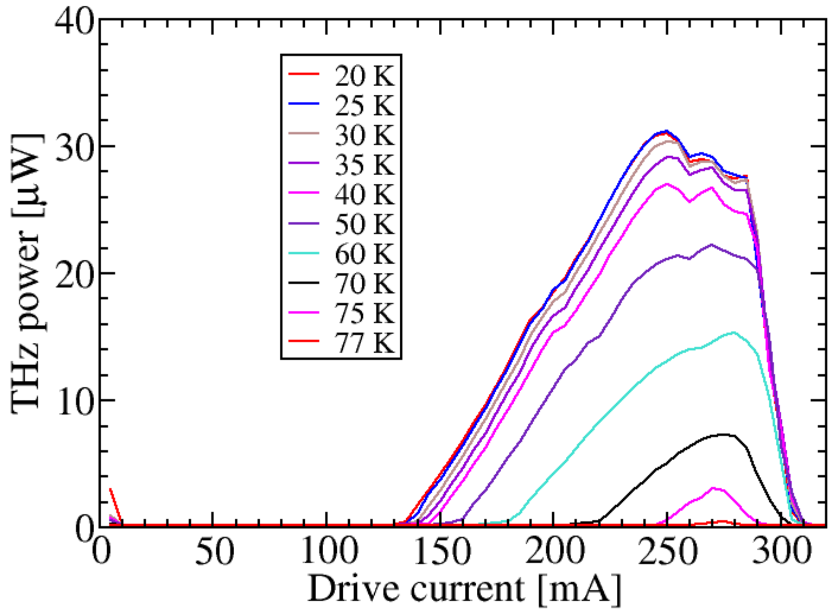
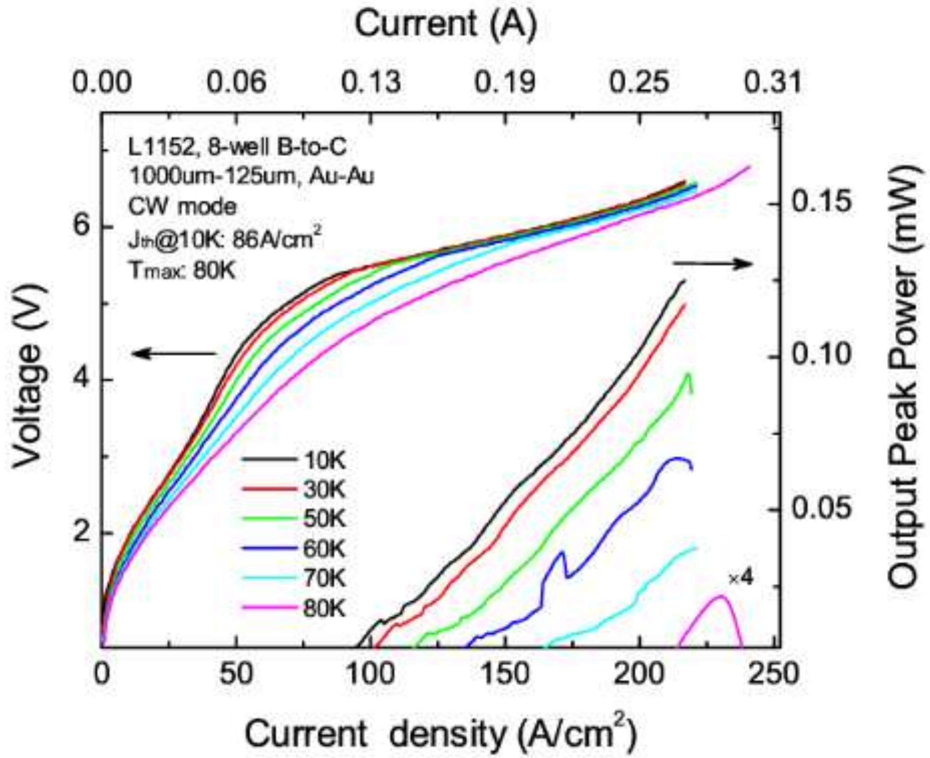


Mounted



Unmounted

Block integration concept works! Minimal change in threshold current or maximum operating temperature.

Collected THz power reduced to ~20%... Optimisation needed!

Waveguide integrated QCLs

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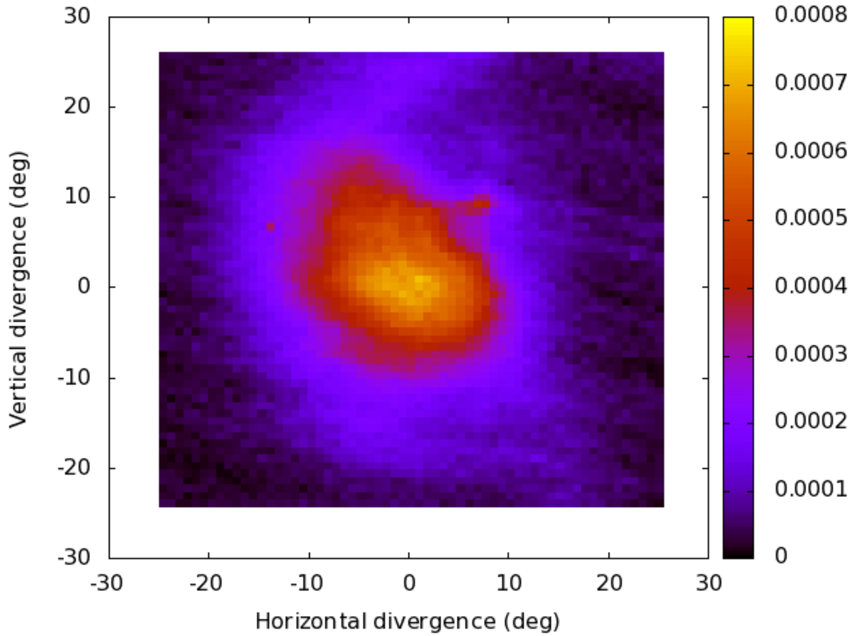

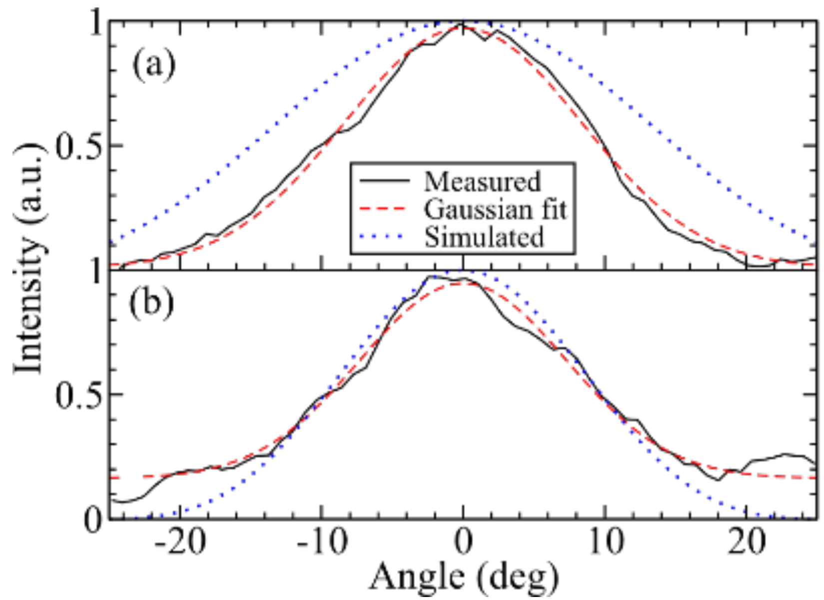

Far-field THz beam-pattern significantly improved:

- Almost Gaussian profile
- Divergence = 17.1-deg (in-plane) / 19.7-deg (growth direction)
- Dramatic improvement over unmounted QCL (~120-deg)
- Underpins future systems with **no external optics**

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

QCL optimisation

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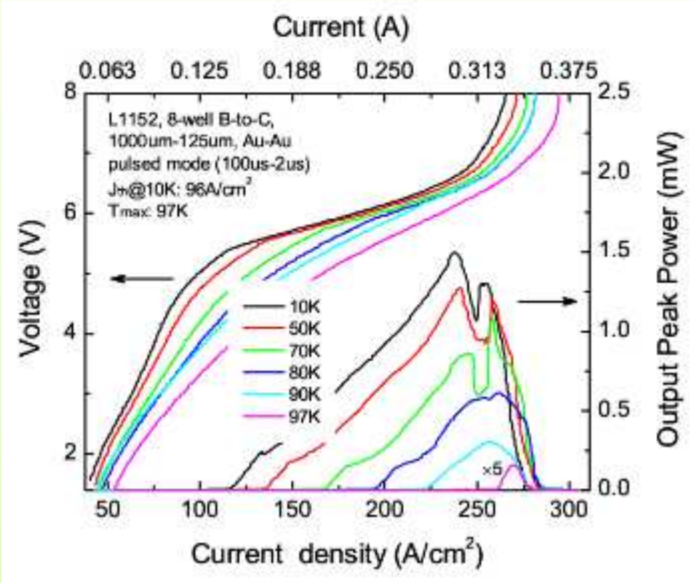
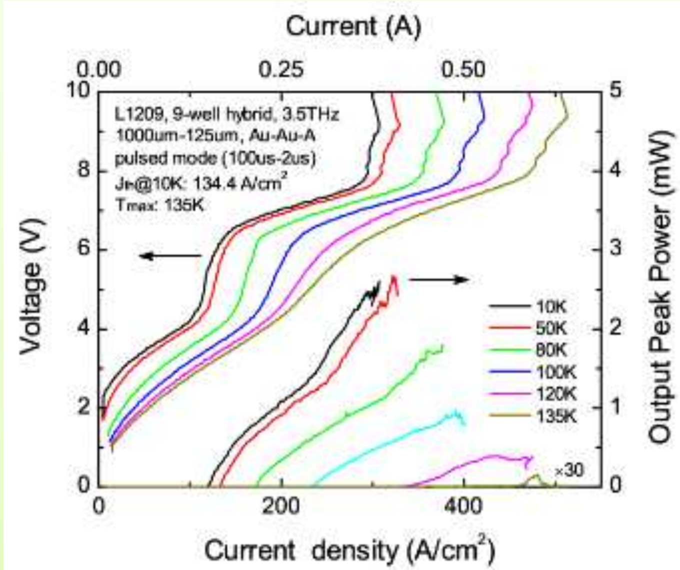
Active region "A"



G. Scalari et al., APL 82, 3165 (2003)

Active region "B"



M. Wienold et al., *Electron. Lett.* **45**, 1030 (2009) [rescaled 3.1 to 3.5 THz]

System	*f* (THz)	T_{max} (K) (pulsed/cw)	J_{th} (A/cm^2, 10K) (pulsed/cw)	P_{max} (mW, 10K) (pulsed/cw)	P_{dis} (W, 10K) (pulsed/cw)
A	3.27–3.45	97/80	**96/86**	1.5/0.12	**1.79**
B	3.31–3.58	**135/86**	134/133	**2.6/0.41**	3.10

Feedhorn integration

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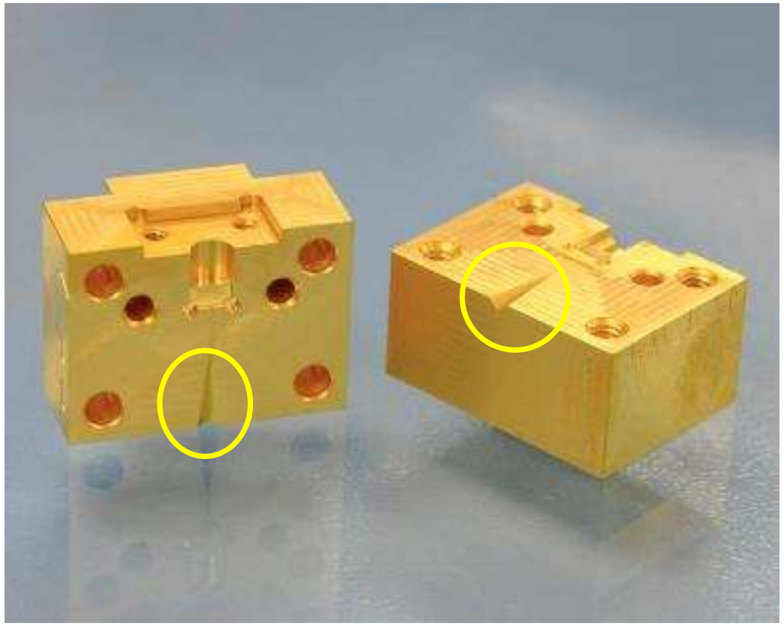
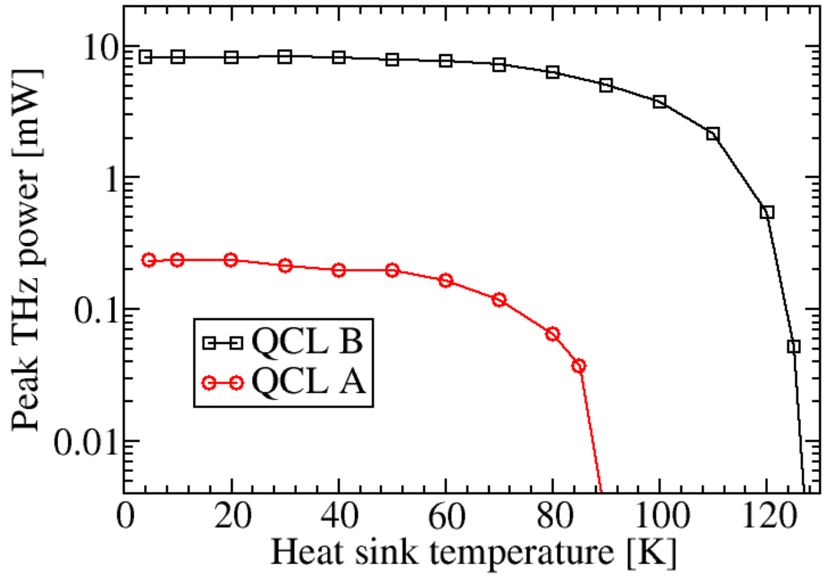
Diagonal horn-antenna with optimised QCL + waveguide





Preliminary results:

- 8.2 mW output power
- 127 K pulsed operation (80 K, cw)
- 6.2 mW @ 77 K (1 mW, cw)

Thin QCL substrates

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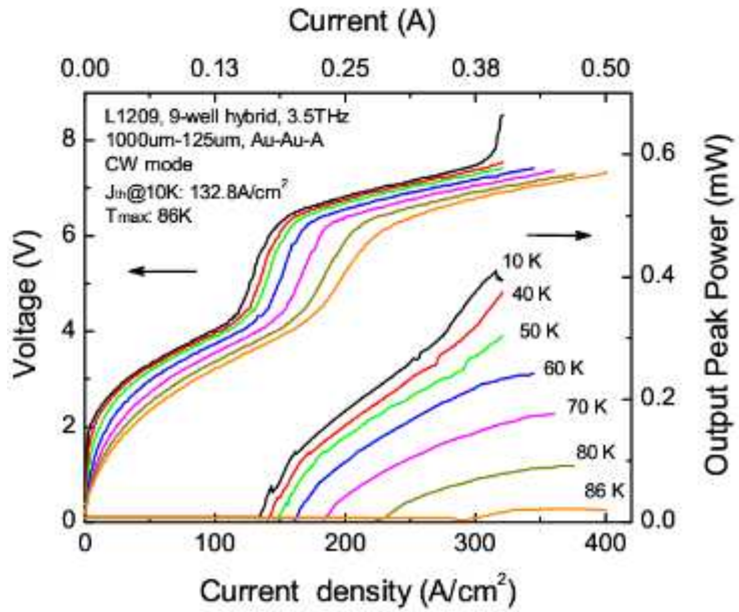
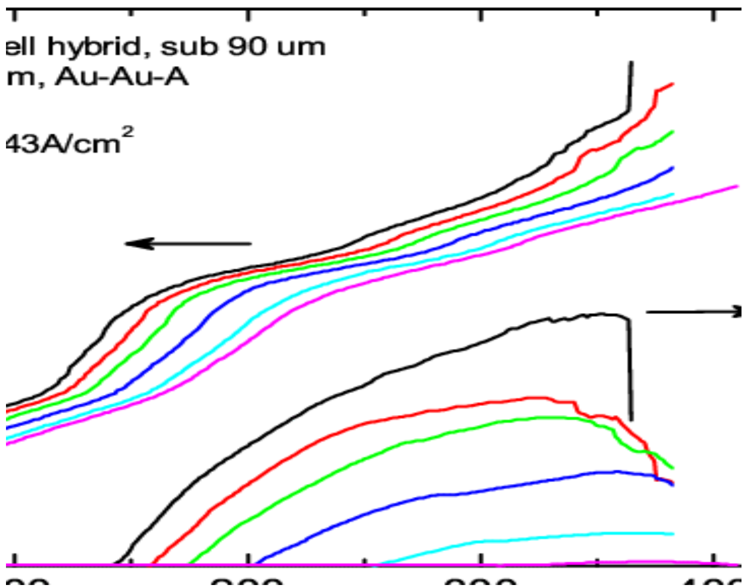
Reducing substrate thickness allows direct mounting of QCL in waveguide channel, and reduced power dissipation.





Device: 1000μm×125μm×15μm

Substrate: 180 μm

T_max: 86 K

P_dis: 3.1 W

Device: 980μm×75μm×15μm

Substrate: 90 μm

T_max: 85 K

P_dis: 2.3 W

Cryo-cooler performance

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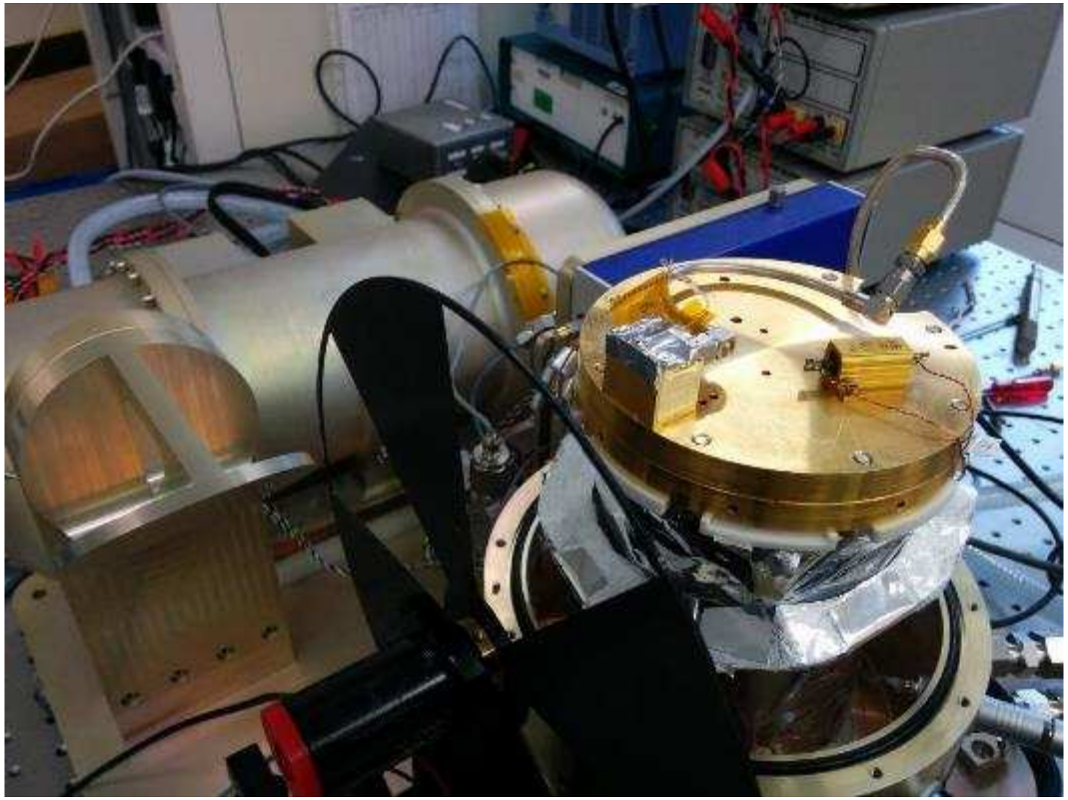
3.5-THz QCL mounted in RAL Sterling cooler



Cryo-cooler performance

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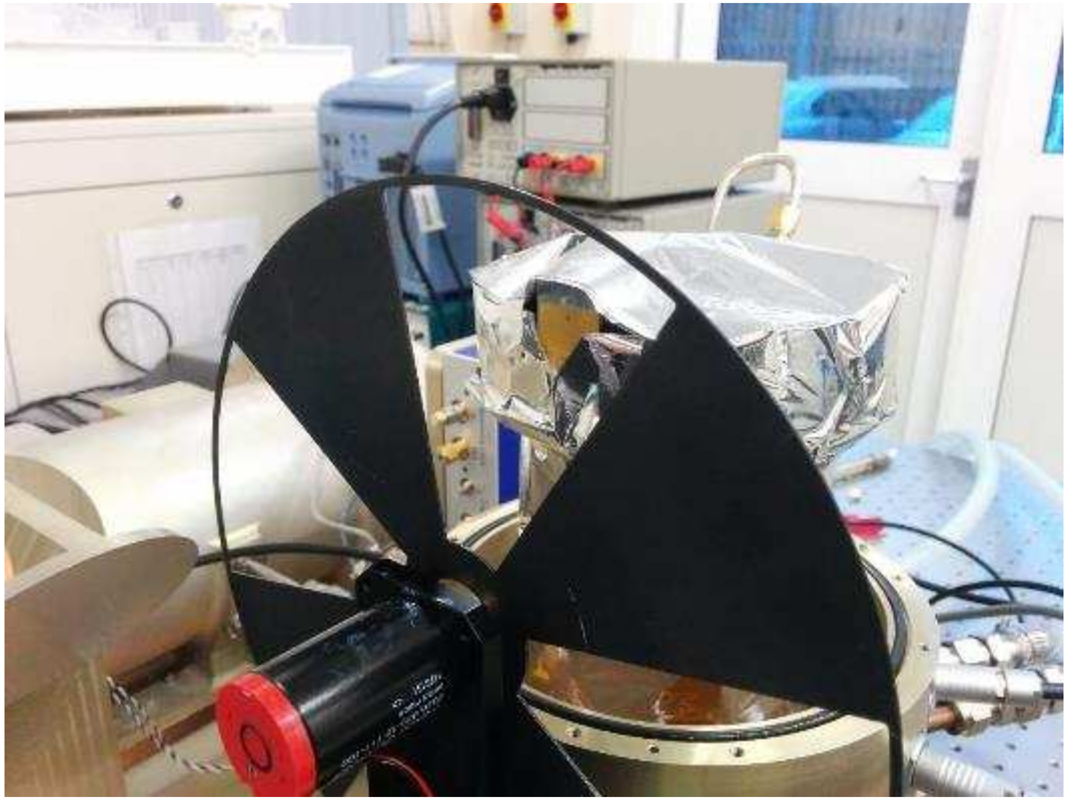
3.5-THz QCL mounted in RAL Sterling cooler



Cryo-cooler performance

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3.5-THz QCL mounted in RAL Sterling cooler

•Stable QCL operation at 65 K

•1 mW THz power out-coupled from cryo-cooler into detector

Dual-feedhorn design

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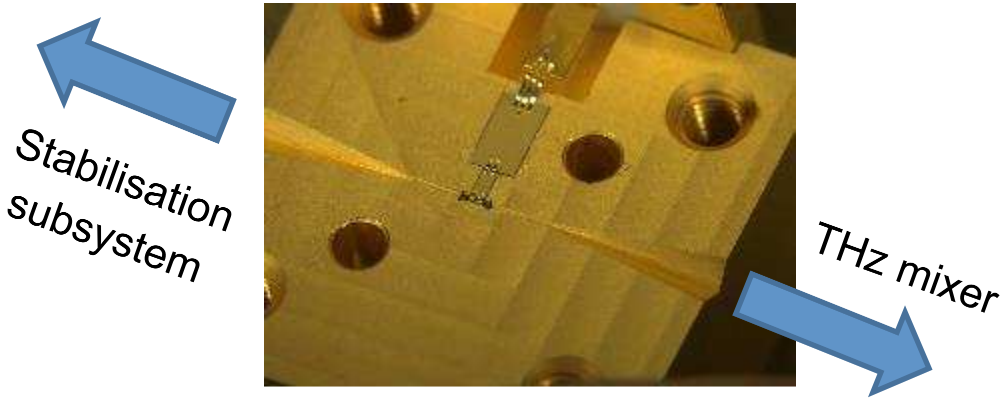
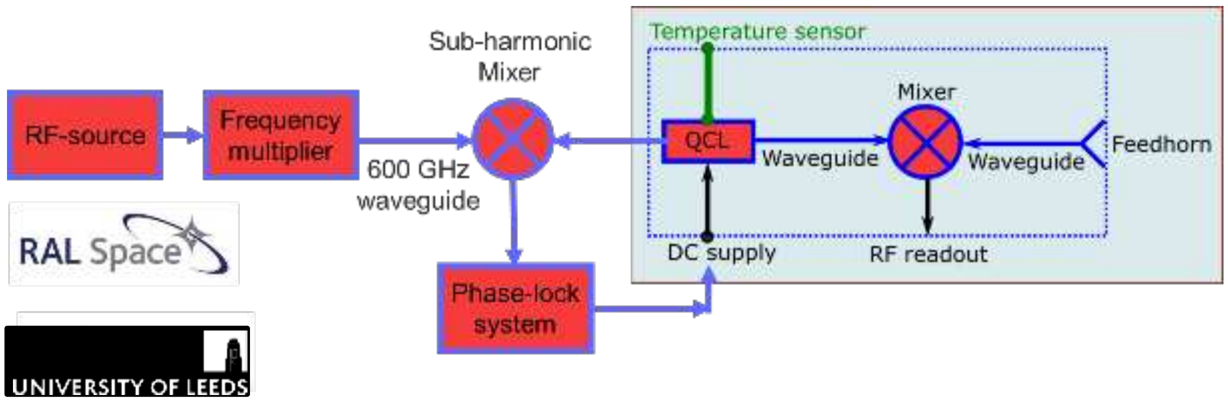
- Dual-feedhorn design enables simultaneous access to **both facets** of QCL
- Will enable coupling with mixer and stabilisation subsystem





Dual-feedhorn design

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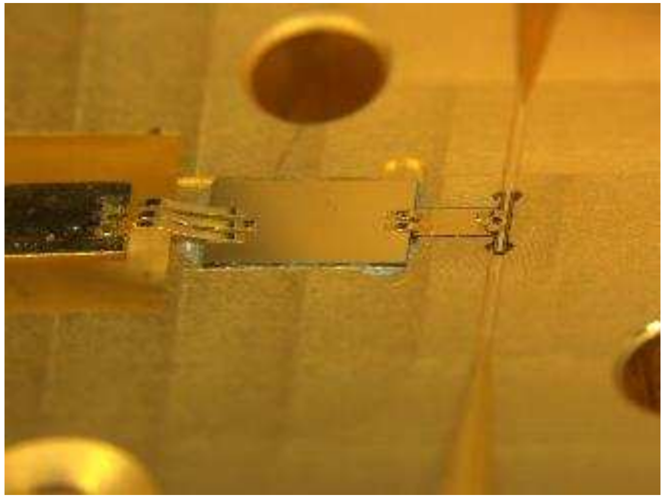
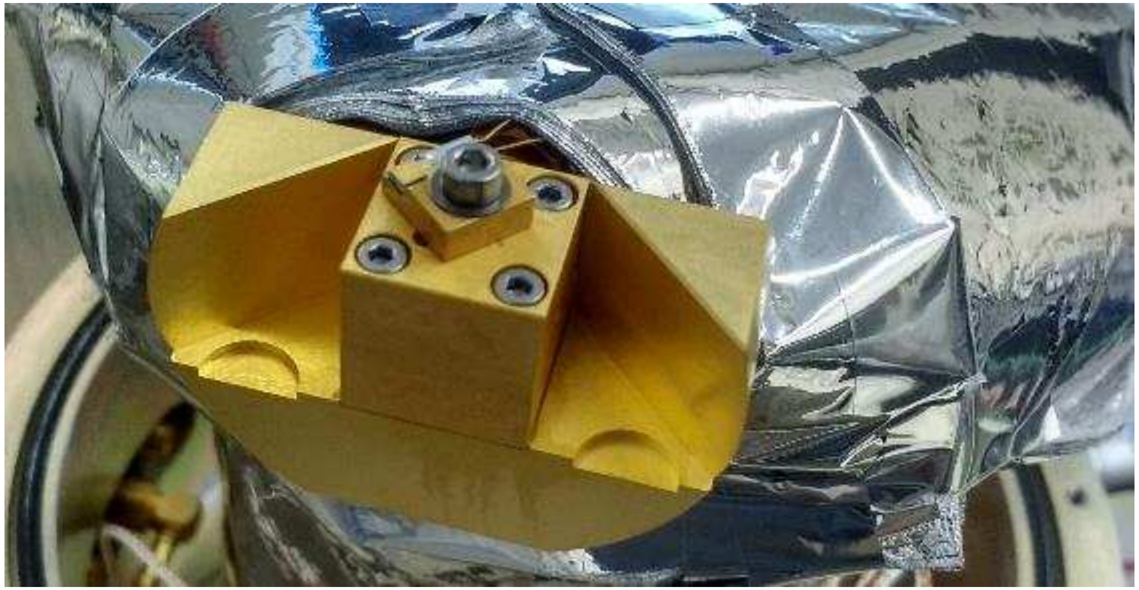
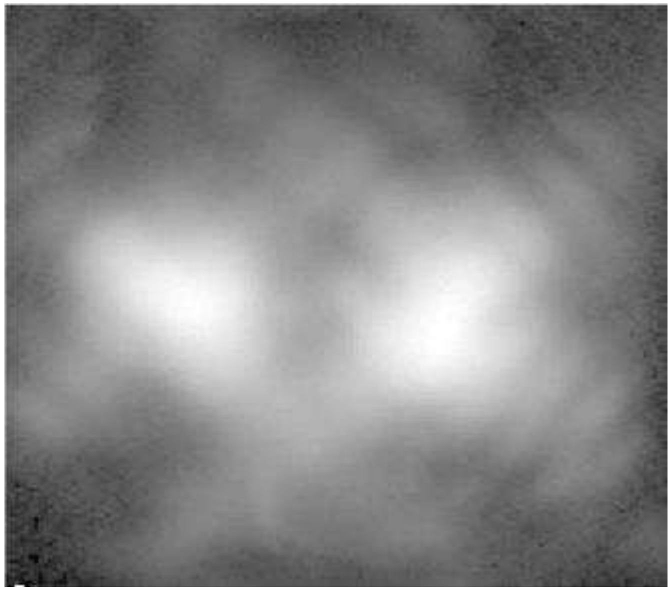
- Cryo-cooler operation demonstrated
- Diffraction/interference pattern observed
  - Coherent beam collection from both facets







Future perspectives

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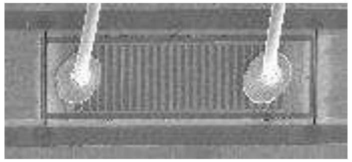

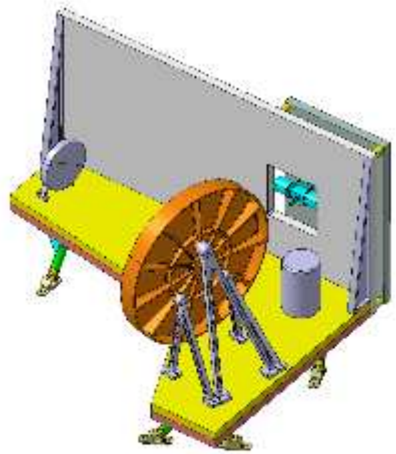

- Successful waveguide integration of QCLs has been demonstrated
- Key subsequent development steps:
  - Complete system breadboarding
  - Stabilisation subsystem integration
  - Mixer integration
  - Airborne/in-orbit demonstration

Summary

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- **LOCUS:** A breakthrough THz limb sounder concept
- **THz QCLs:** The first compact, yet powerful direct THz sources
- **Waveguide integration of QCLs**: Progress towards complete THz radiometry systems in compact waveguide blocks, underpinning future satellite applications**.**

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•University of Leeds (*Y. J. Han, J. R. Freeman*, *L. H. Li*, *E. H. Linfield, A. G. Davies*)