Integrated terahertz systems for satellite applications

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Overview

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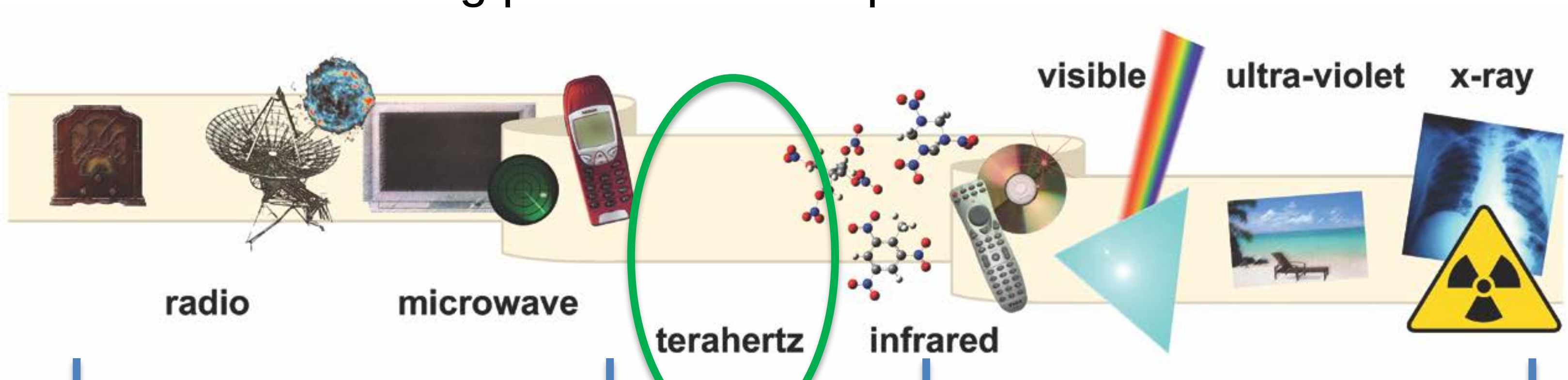
- Terahertz (THz) radiation and trace-gas sensing
- The LOCUS instrument
- Terahertz Quantum Cascade Lasers (QCLs)
- Integrated THz systems

THz radiation sources

The meeting point between optics and electronics



Electronic (classical) oscillators

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

Optical (quantum) oscillators

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

The "THz gap":
f = 2–10 THz

Properties and applications of THz waves

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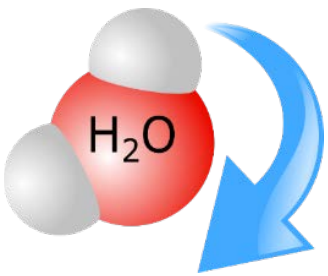
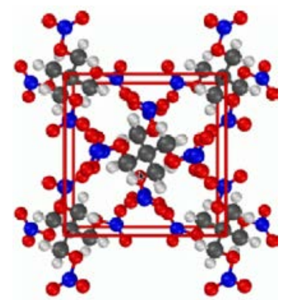
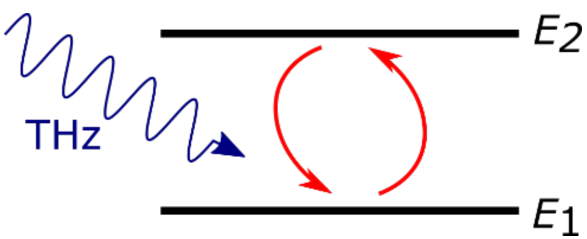
THz radiation highly sensitive to:



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

Low-Cost Upper Atmosphere Sounder (LOCUS)

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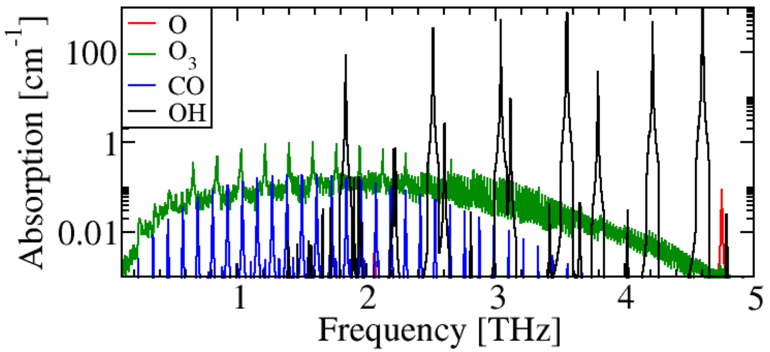
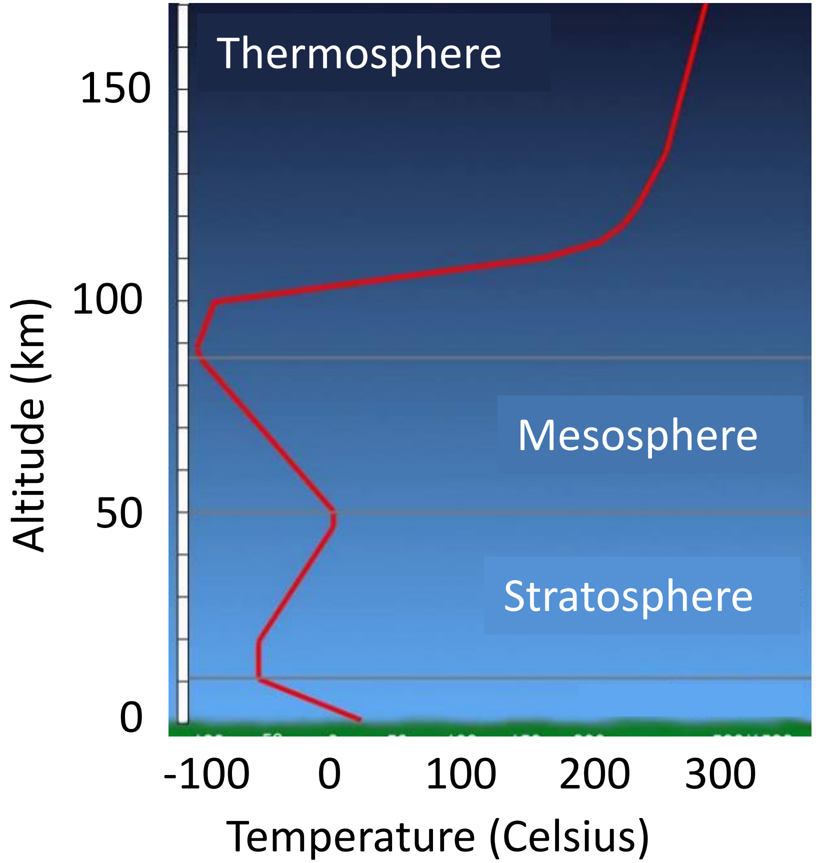
A breakthrough THz remote sounder

- 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

Low-Cost Upper Atmosphere Sounder (LOCUS)

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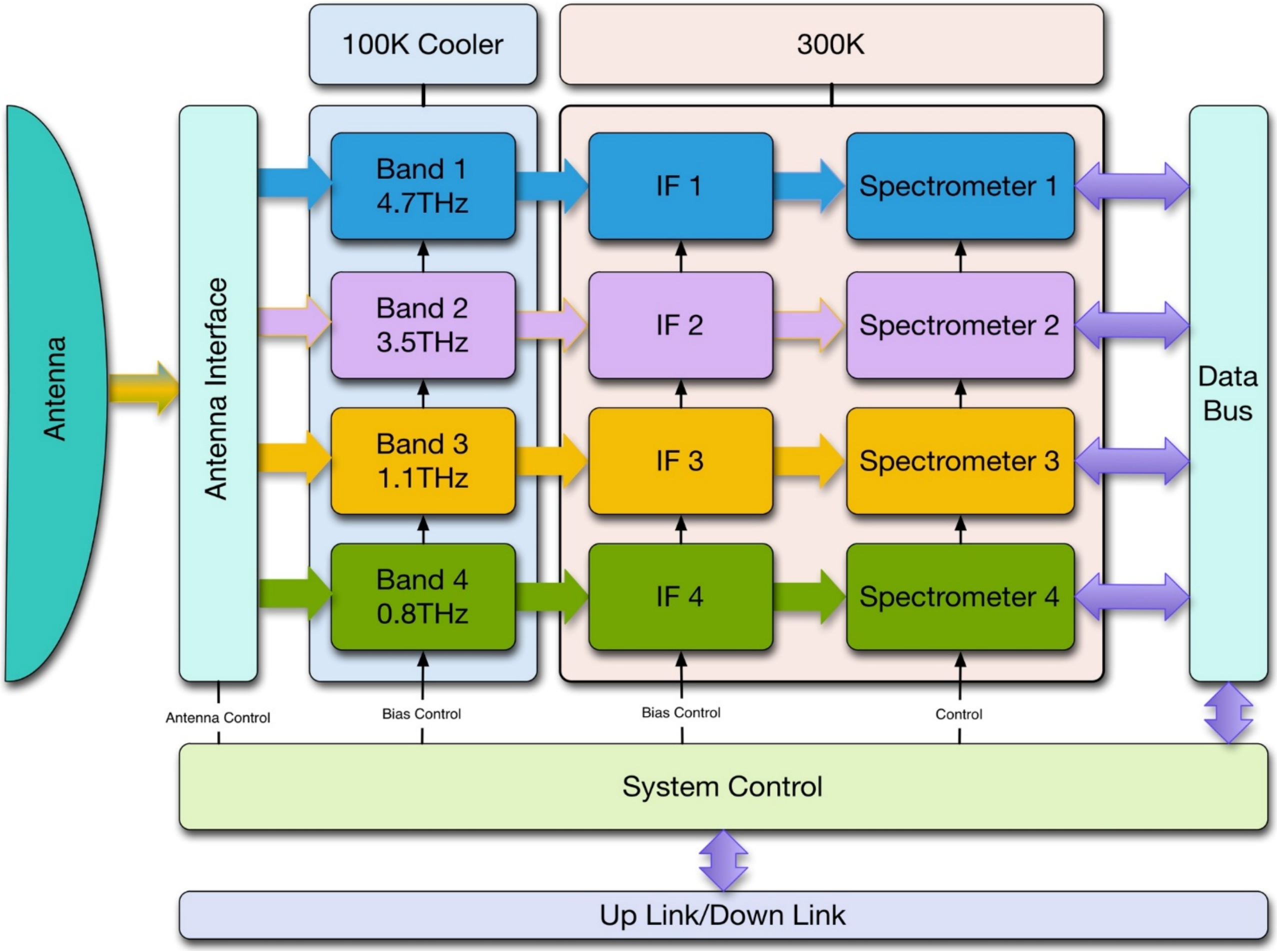

System schematic

LOCUS Core Technology

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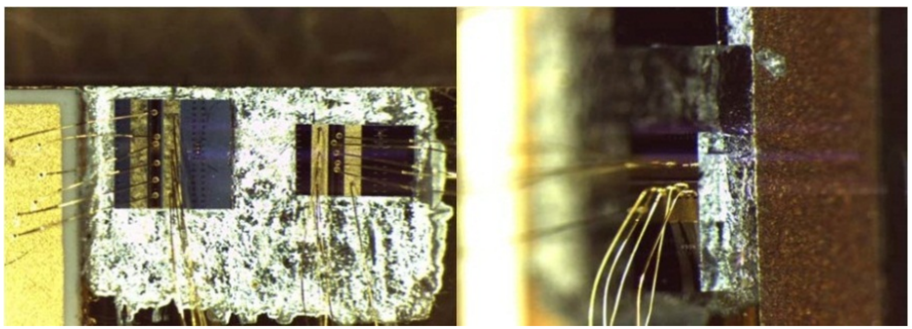
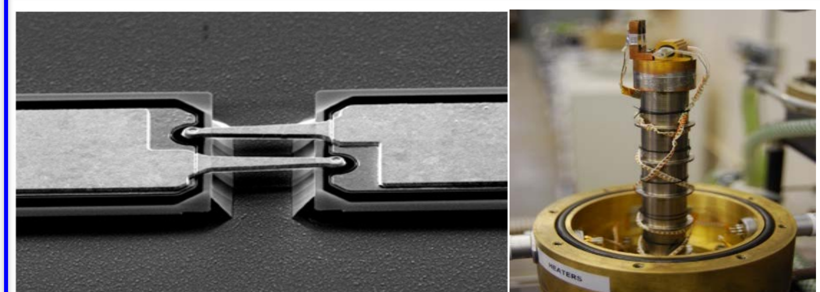
3.5 & 4.7 THz QCL
Local Oscillators
University of Leeds



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

Quantum cascade lasers

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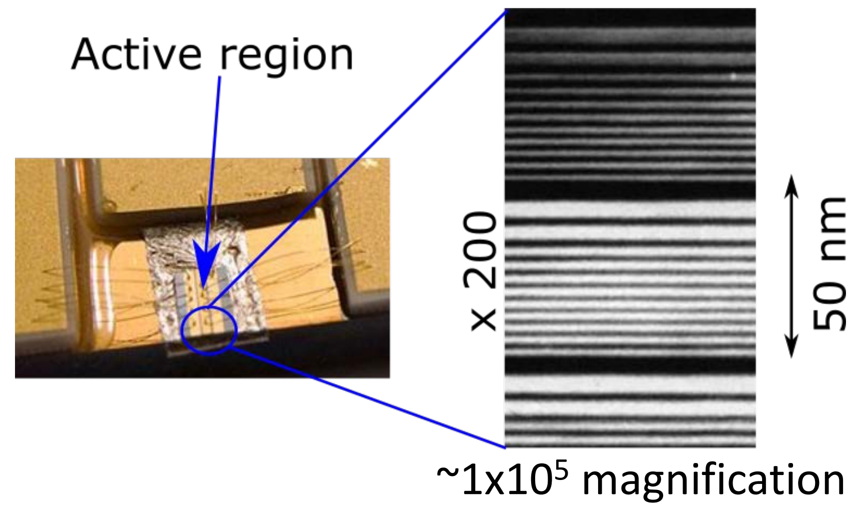
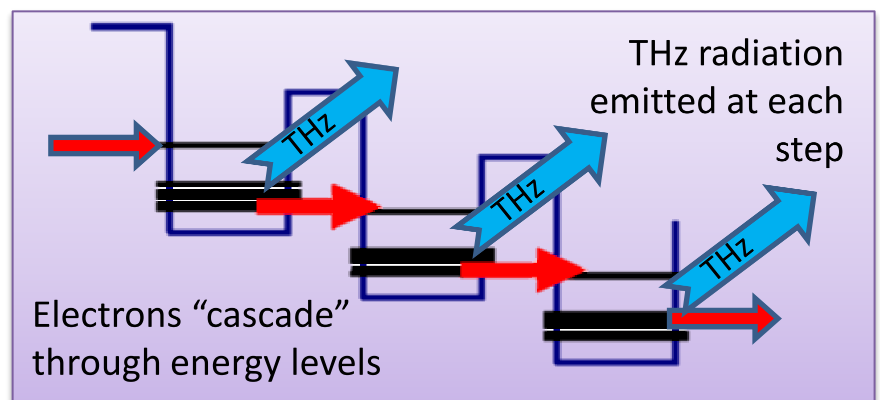
The first powerful and compact continuous-wave THz source:

- ~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

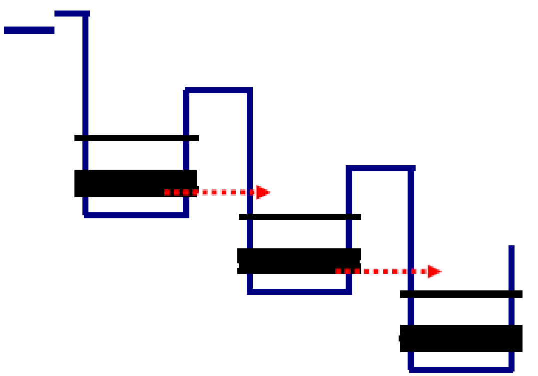


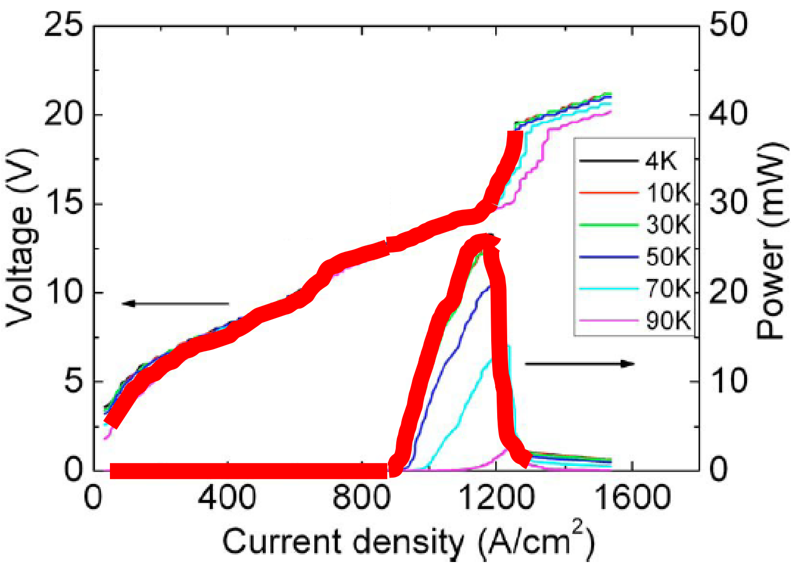


Electronic behaviour

Peak THz power corresponds to efficient injection of current:

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





Gas sensing using THz QCLs

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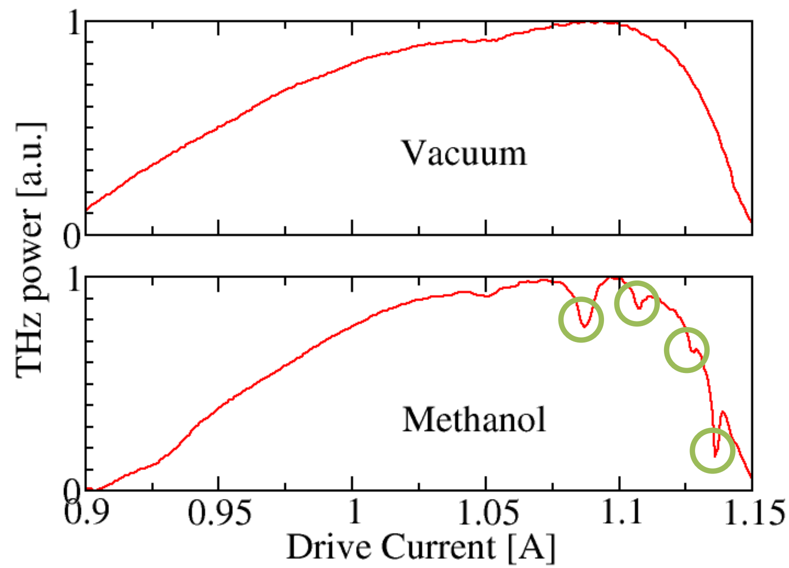
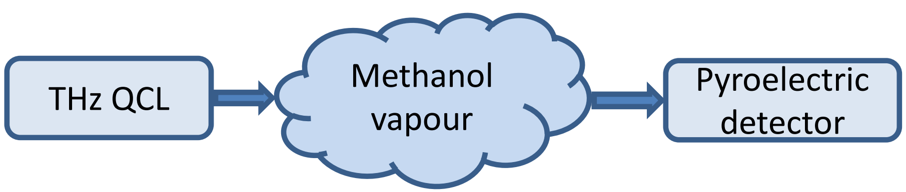
UNIVERSITY OF LEEDS Challenger Laboratory

- Transmission spectroscopy using 2.6 THz QCL – first demonstration in UK
- High QCL power enables low vapour pressure (5 Torr)
- ~20 MHz resolution (free-running QCL)
- 4 GHz tuning bandwidth





THz radiometer requirements

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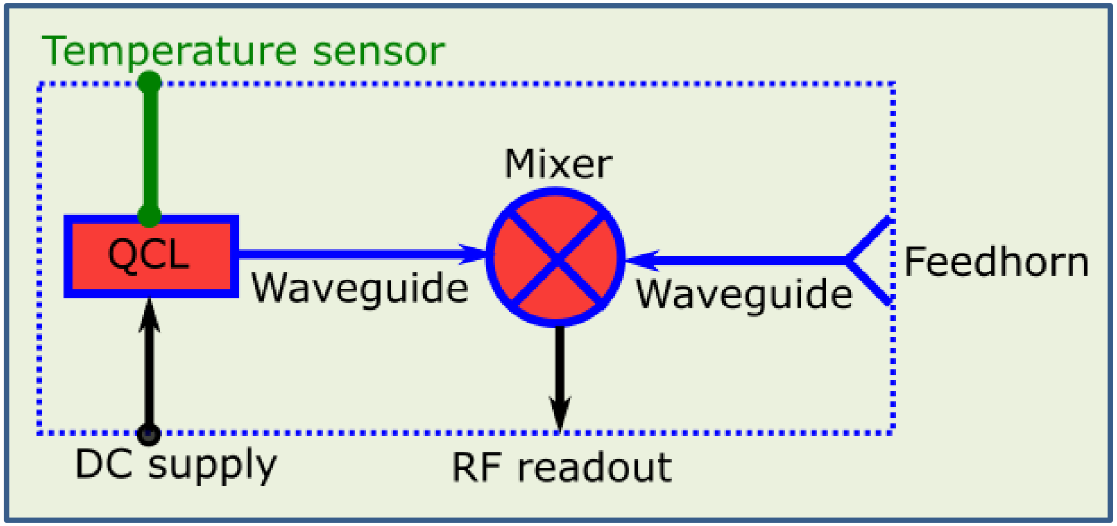
- 1 mW local-oscillator (QCL) output power
- Compact, low-mass
- Low input power (< 5 W)
- Mechanically robust
- Close integration of components



Recent integration approaches

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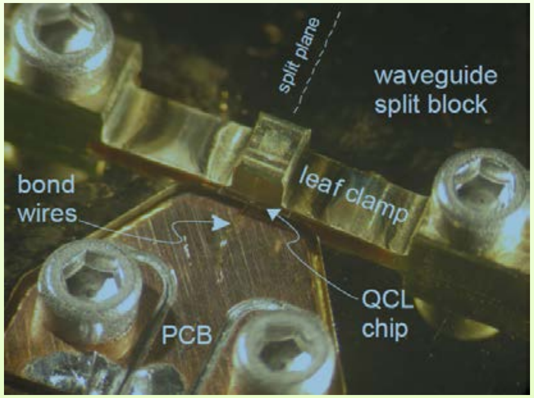
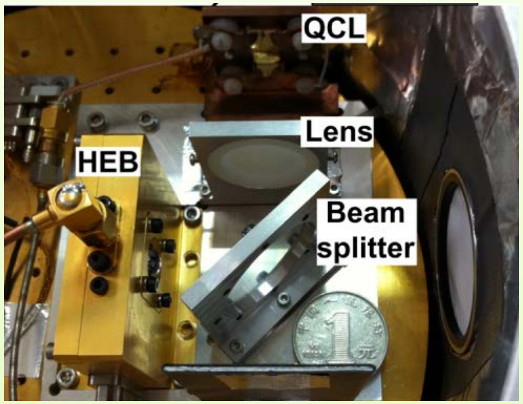


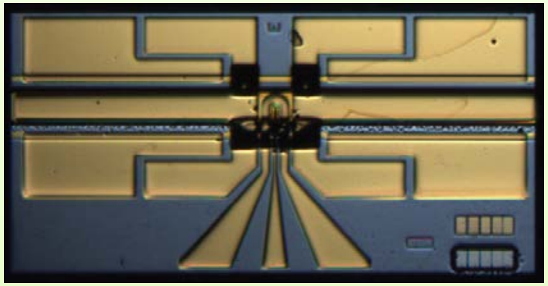
QCL
+ waveguide
+ horn antenna

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 integration)

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

LOCUS integration design

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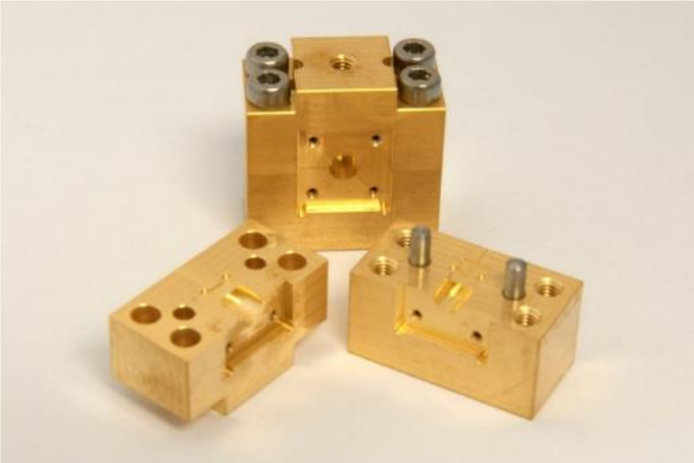
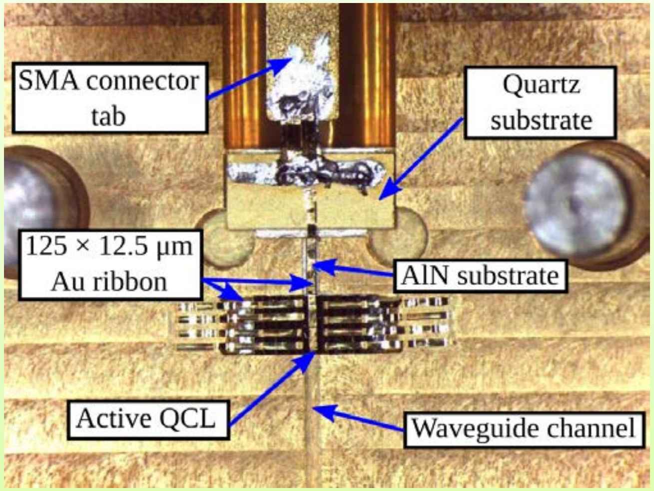
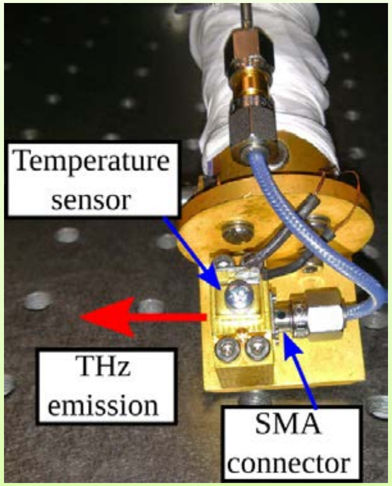
- Double metal 3.5 THz QCL
- Precision-micromachined 300 × 150 μm Cu waveguide
- High-frequency electronic ribbon-bonding + SMA
- Integrated temperature sensor







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

Spectral coverage

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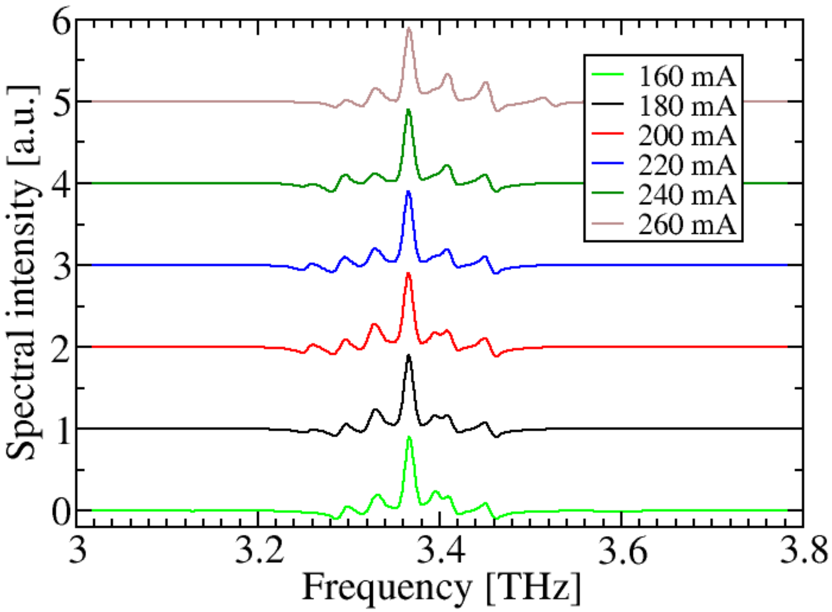

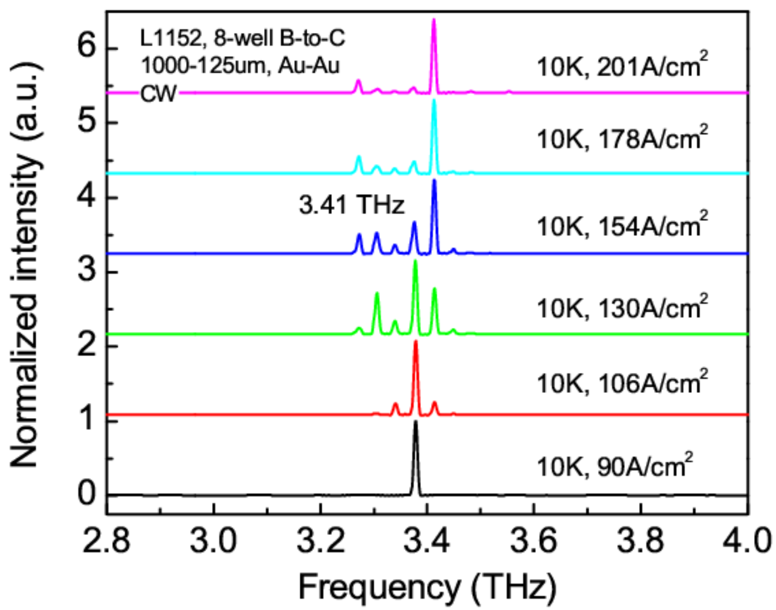

Mounted

Unmounted

Electrical/thermal performance

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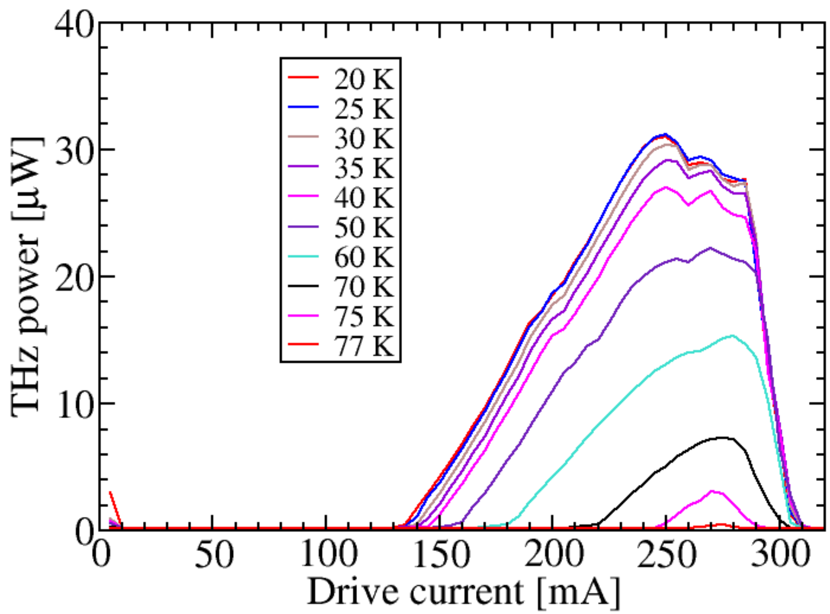
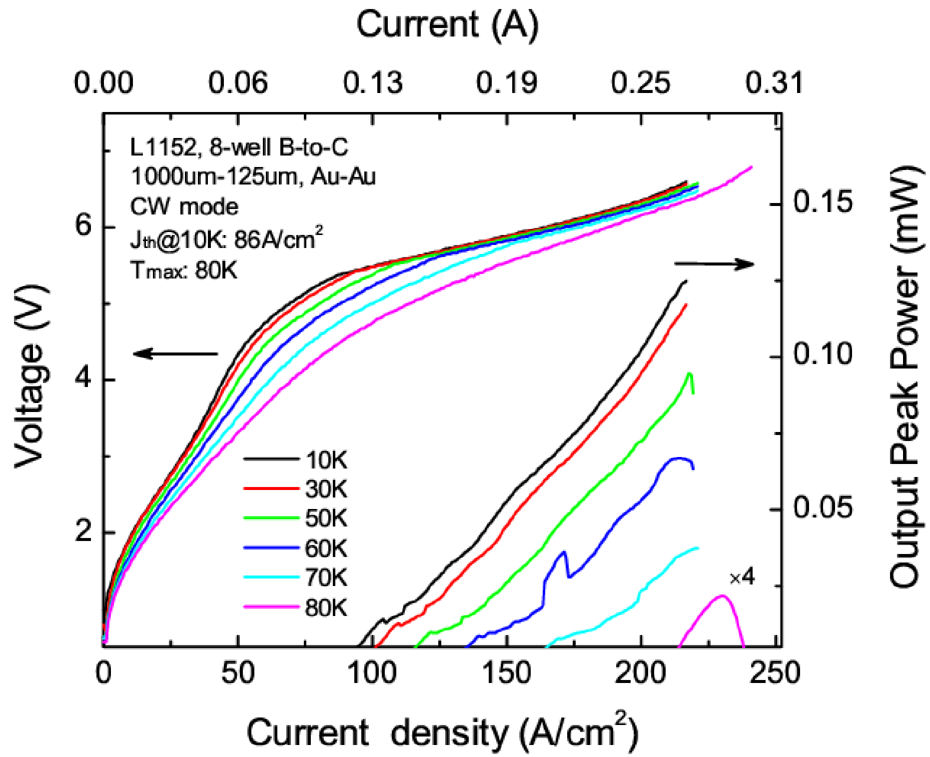


Mounted



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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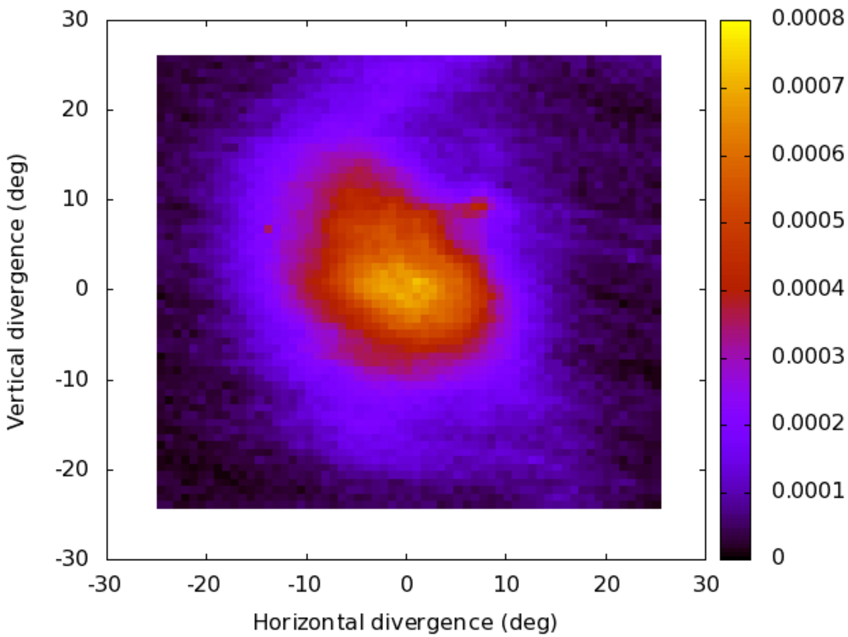

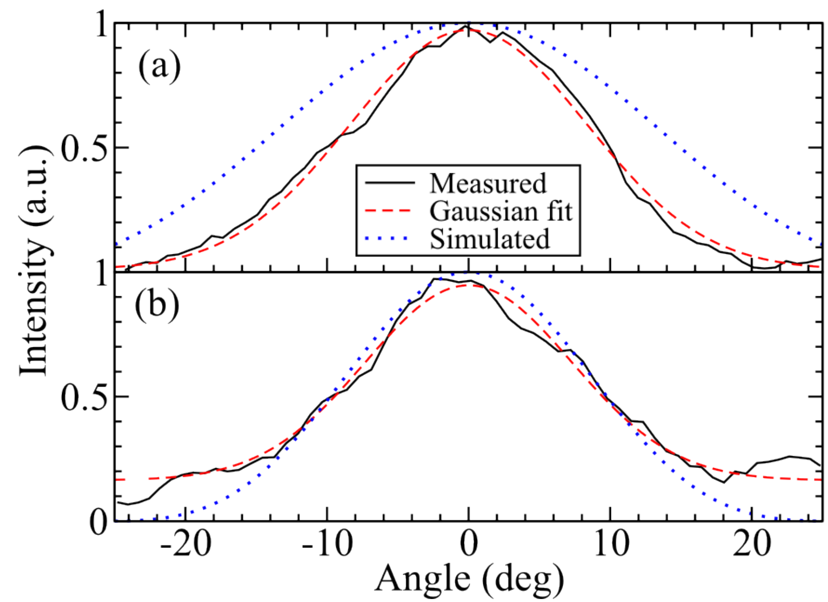

Far-field THz beam-pattern significantly improved:

- Almost Gaussian profile
- Divergence = 17.1-deg (in-plane) / 19.7-deg (growth direction)
- Dramatic improvement over DM (~120-deg)

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

Active region designs

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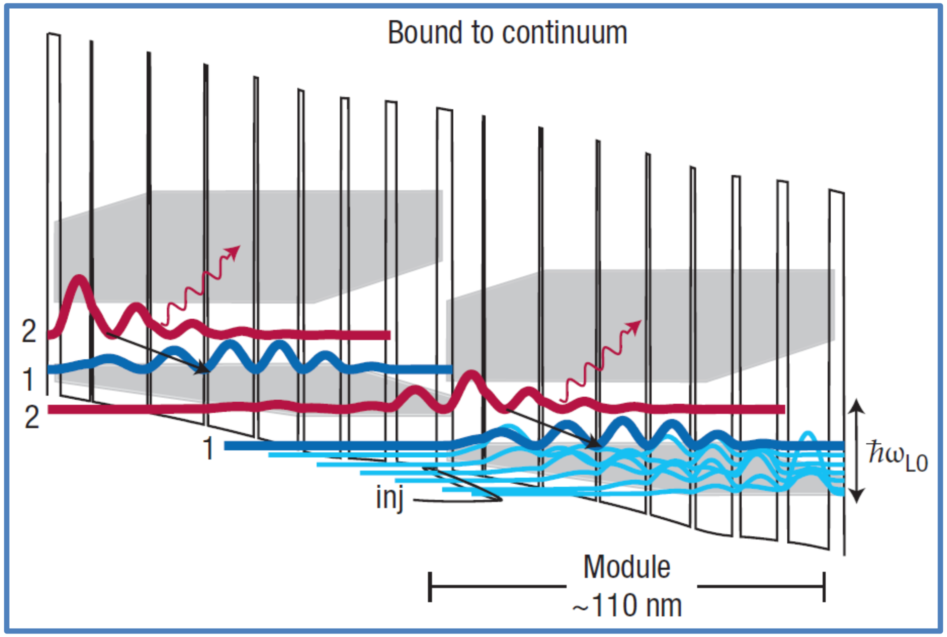
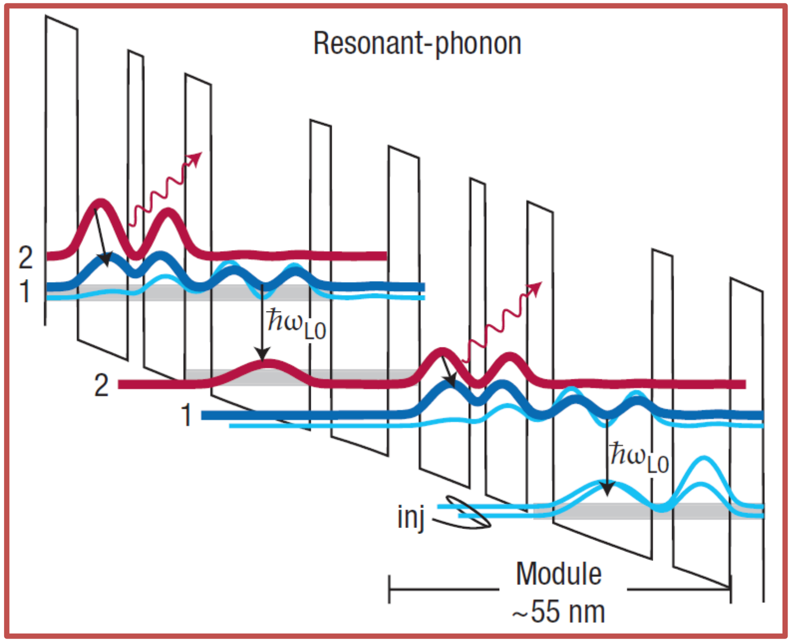
Two main design schemes used in QCLs





- Elastic scattering within miniband
- Low electric field
- Selective injection

- Electron–LO-phonon scattering
- Maintains population inversion at high temperatures

A *hybrid BTC/RP QCL* design delivers high output powers AND continuous-wave operation

QCL optimisation

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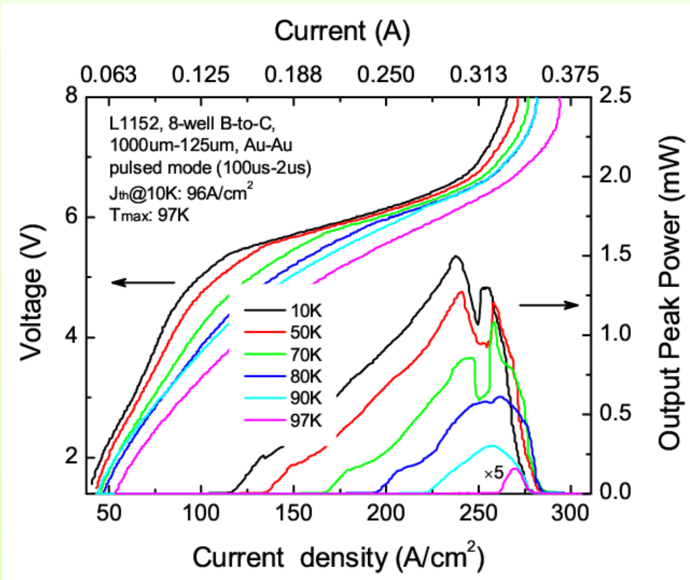
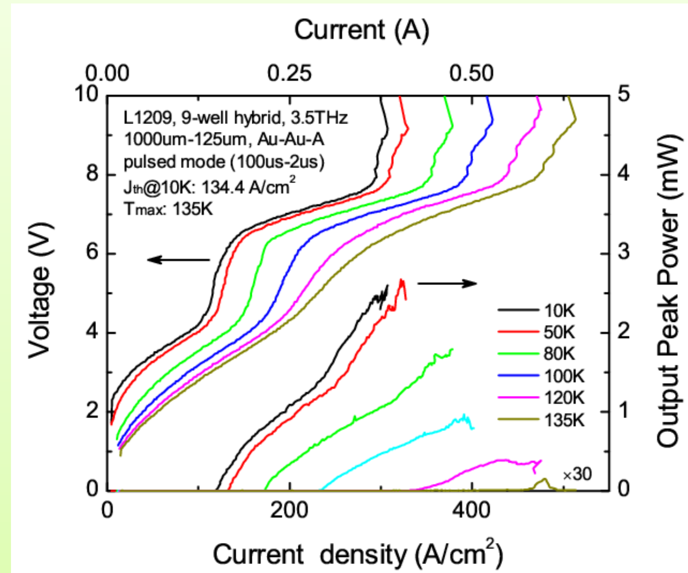
Active region "A"



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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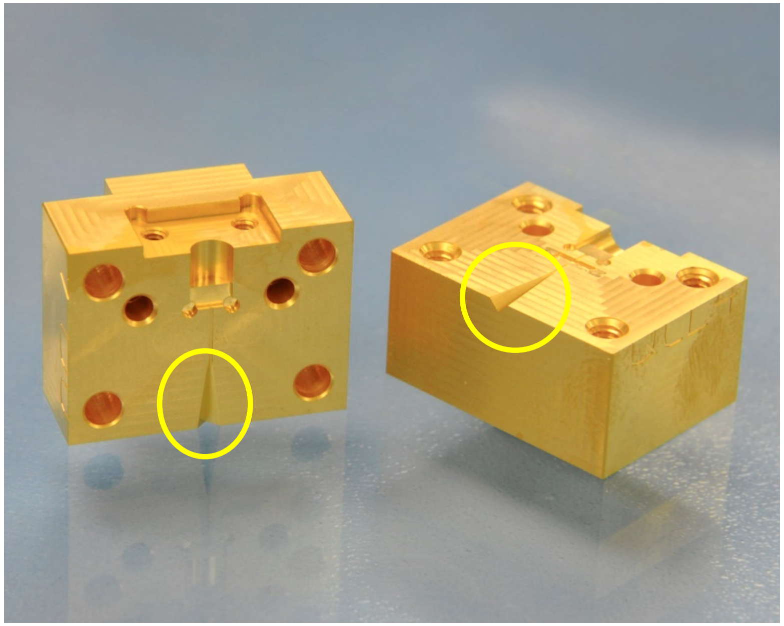
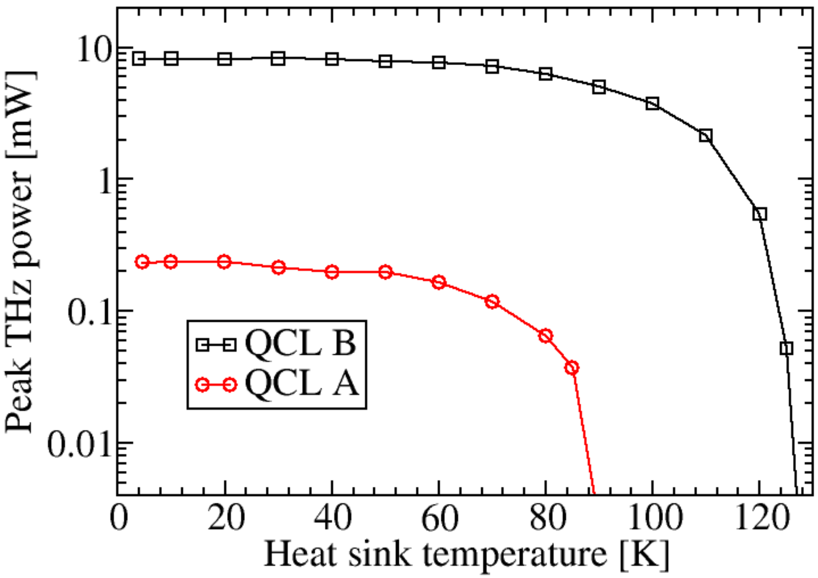
Diagonal horn-antenna integrated with QCL + waveguide





Preliminary results:

- 8.2 mW pulsed power (c.f., 0.32 mW in QCL A)
- 127 K pulsed operation (c.f., 90 K)
- 6.2 mW @ 77 K

Towards integrated THz radiometry systems

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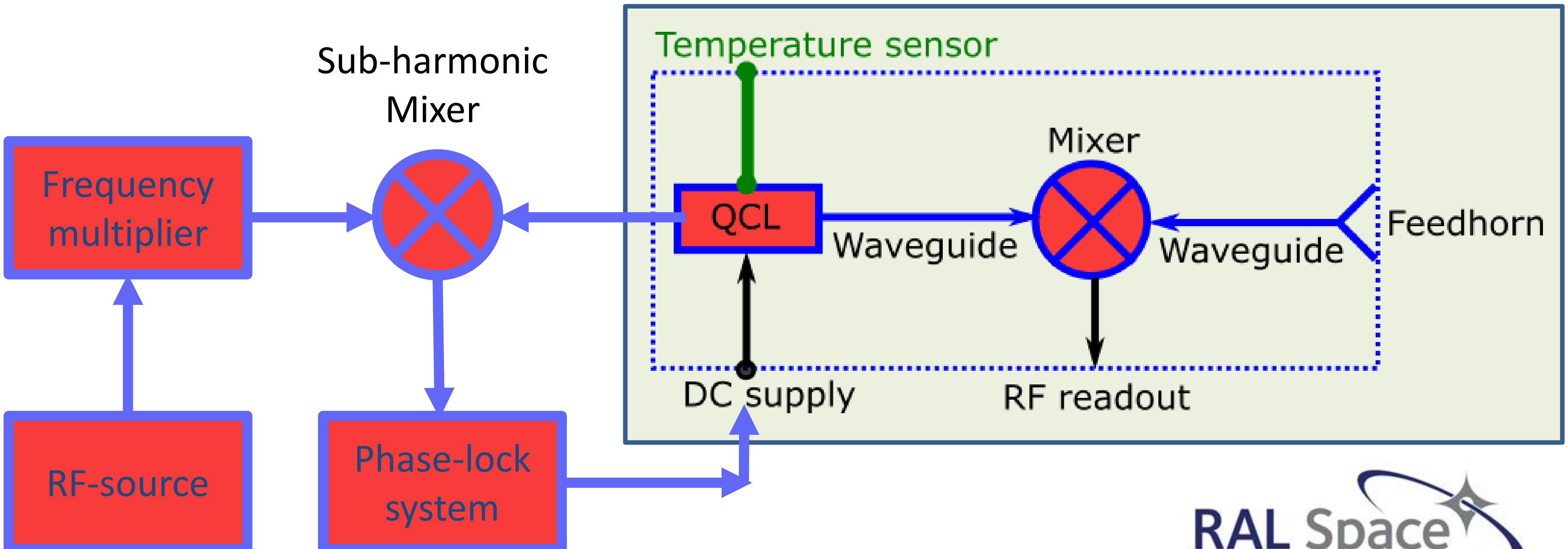
- Precise stabilisation of THz QCL frequency (to ~1 kHz)
- Integration of QCL, mixers and stabilisation electronics
- High-sensitivity gas spectroscopy



RAL Space

Summary

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- **THz-sensors:** fundamental trace-gas studies for space applications
- **LOCUS:** UK collaboration to develop the integrated THz-frequency systems for satellite instrumentation
- **THz QCLs:** UK expertise in developing compact, robust and powerful sources

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•Natural Environment Research Council

•UK Space Agency Centre for Earth Observation Instrumentation (CEOI-ST)

•The Royal Society

•The Wolfson foundation

•EPSRC (UK)

•STFC Centre for Instrumentation