Institute of Microwaves and Photonics
SCHOOL OF ELECTRONIC AND ELECTRICAL ENGINEERING,
FACULTY OF ENGINEERING
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Quantum cascade lasers for THz Heterodyne Sounders

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The need for THz Instrumentation

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For Earth Observation and Planetary Science applications, there is a need to probe molecules that have transitions at THz frequencies, e.g.:

O – 4.745 THz

OH – 3.544 THz

HO_2 – 3.543 THz; 3.544 THz

An ideal approach for this is heterodyne detection (e.g. with a Schottky diode).

– see: *Brian Ellison (RAL Space), 'Instrumentation for 1–5 THz Heterodyne Sounders'*

But, this requires a compact, local oscillator…

And therein lies one challenge…

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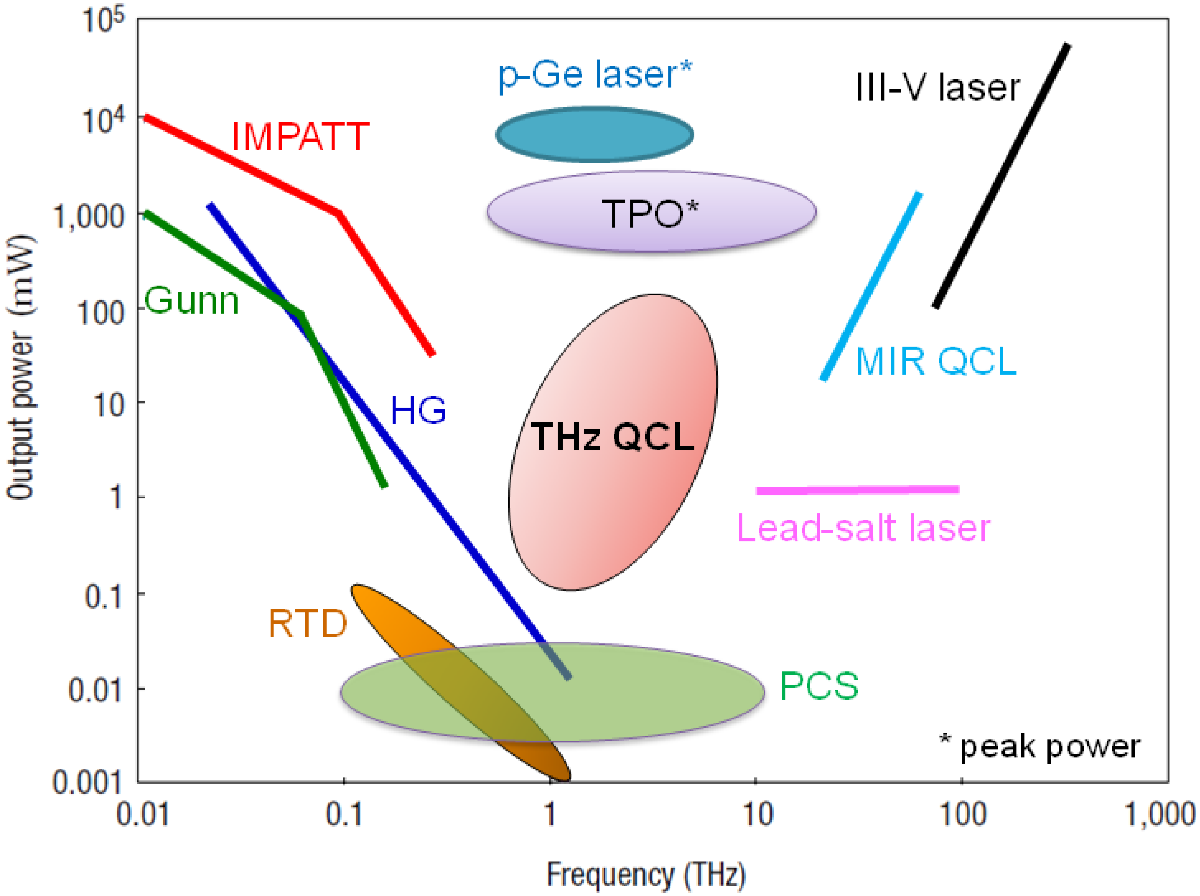

IMPATT – Impact Ionization Avalanche Transit-Time diode

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)

The only realistic option for a compact, high power source appears to be the THz quantum cascade laser.

QCL operating principle

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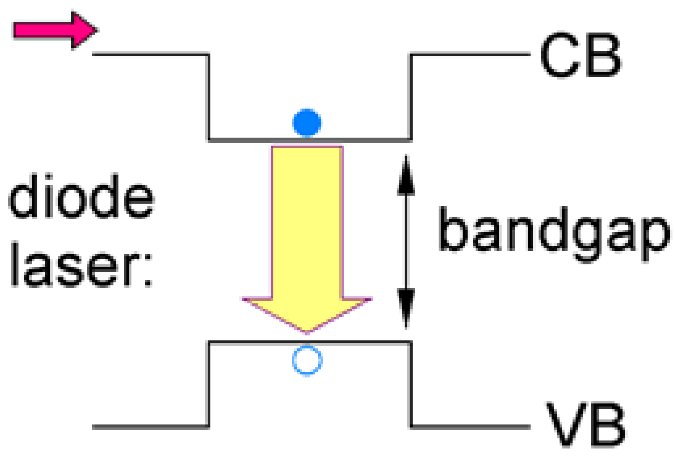
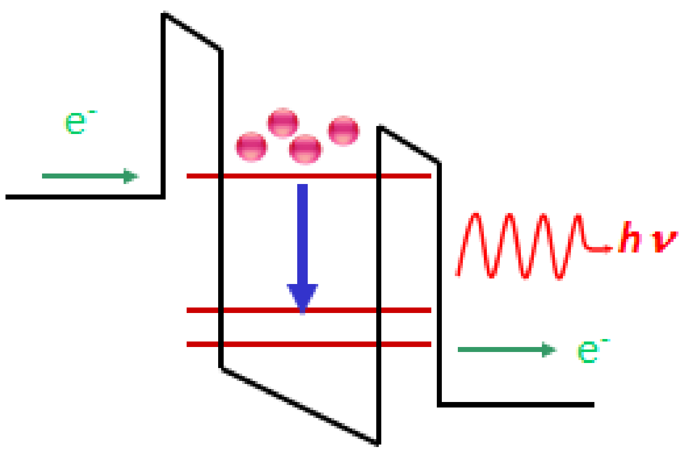


$$\hbar\omega_0 \geq E_g$$



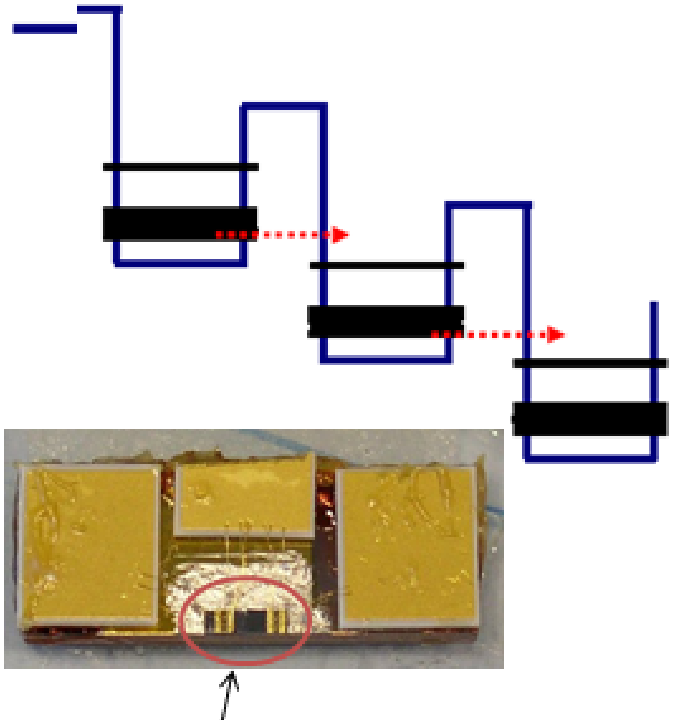
$$\hbar\omega_0 = \varepsilon_3 - \varepsilon_2$$

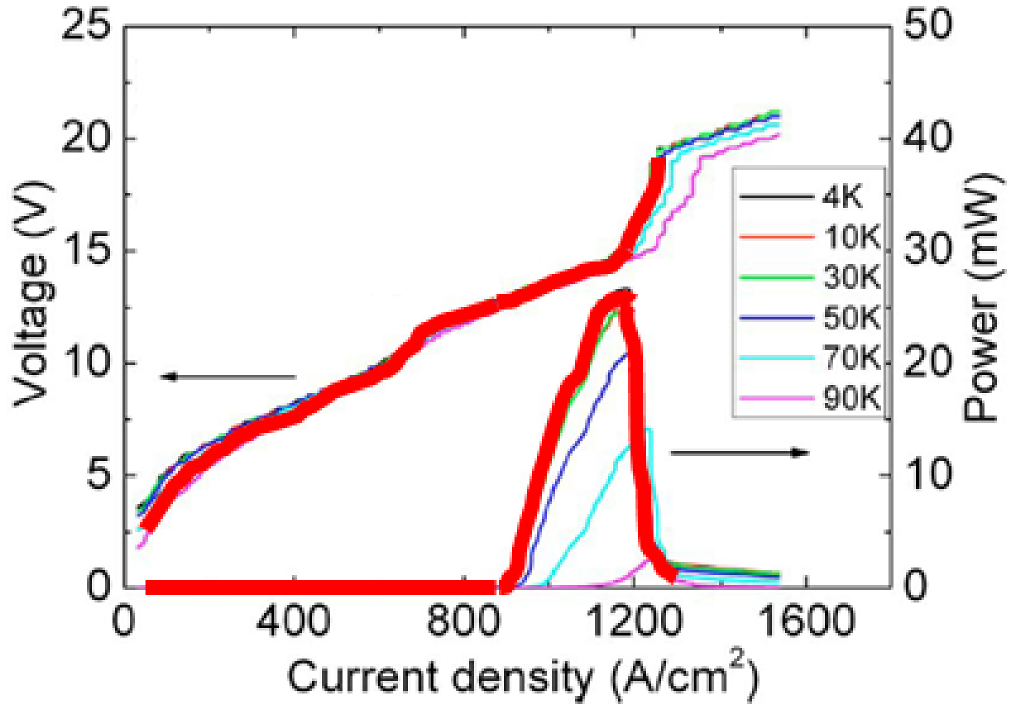
Intersubband transitions in quantum wells

•Long-wavelength emission—Not bandgap limited

•Periodic system: electron 'recycling'

Electronic behaviour





Peak performance corresponds to efficient injection of current

Device dimensions are typically 1 mm × 150 μm × 10 μm

Images of a THz QCL

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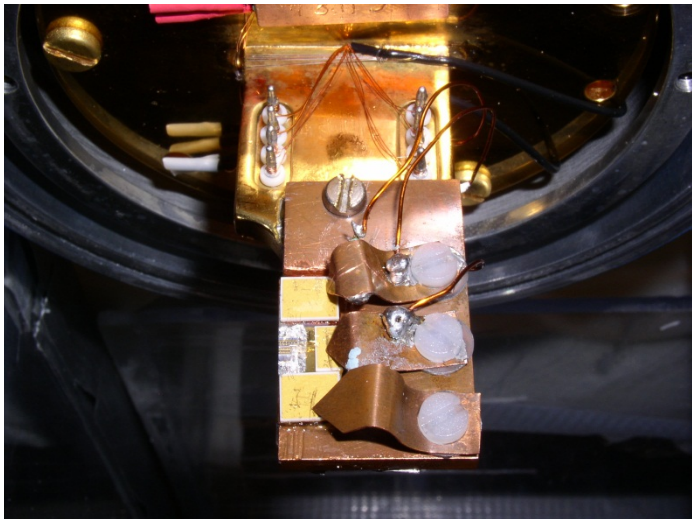
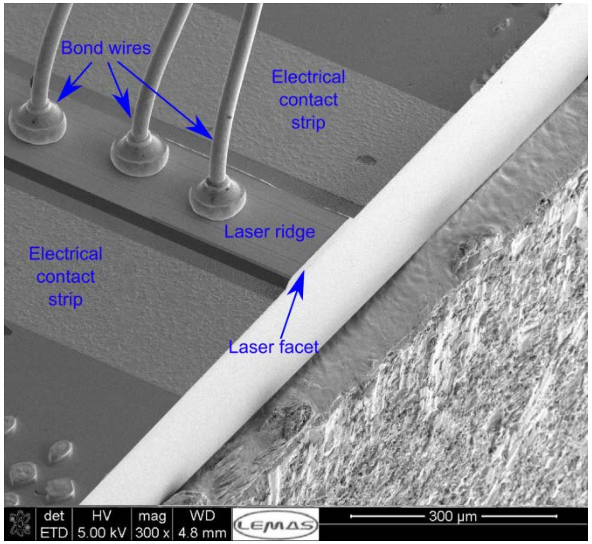
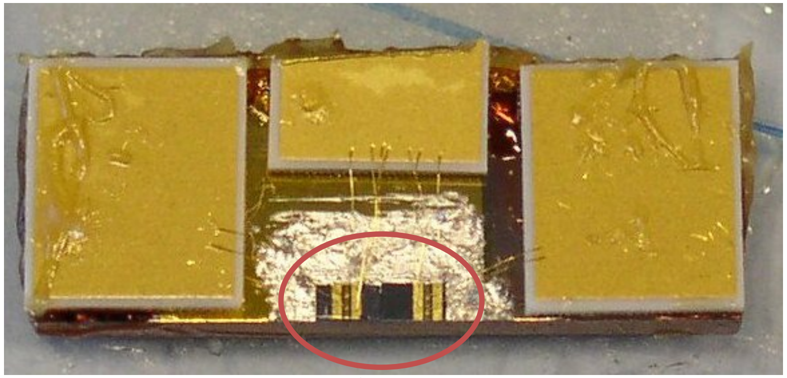
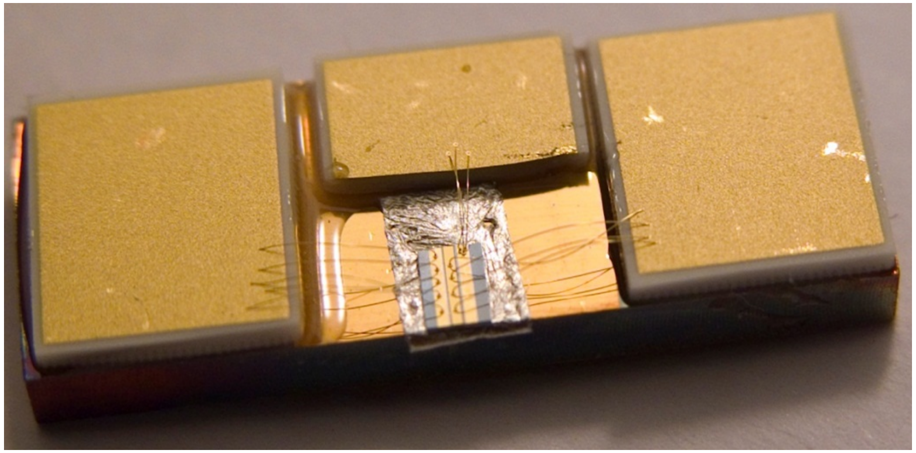






2 QCLs



The first THz QCL

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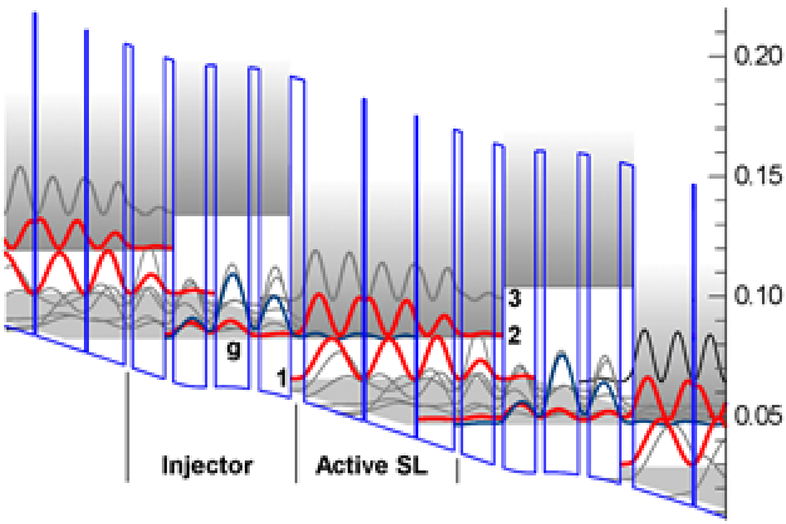

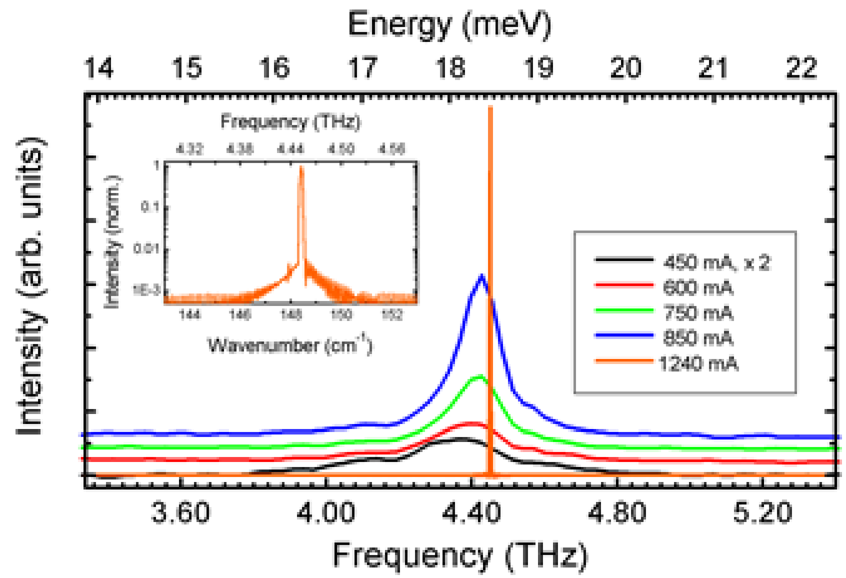

- **Developed in Europe in 2001 by INFM(Pisa)/ Cambridge through an EC Framework V programme ‘WANTED’;**
- **Structure contained 104 repeat periods each 104.9 nm long, and contained barriers of only a few atomic monolayers thick.**

R. Köhler *et al.*, *Nature* 417, 156 (2002); *The Economist*, August 10th, 73 (2002).

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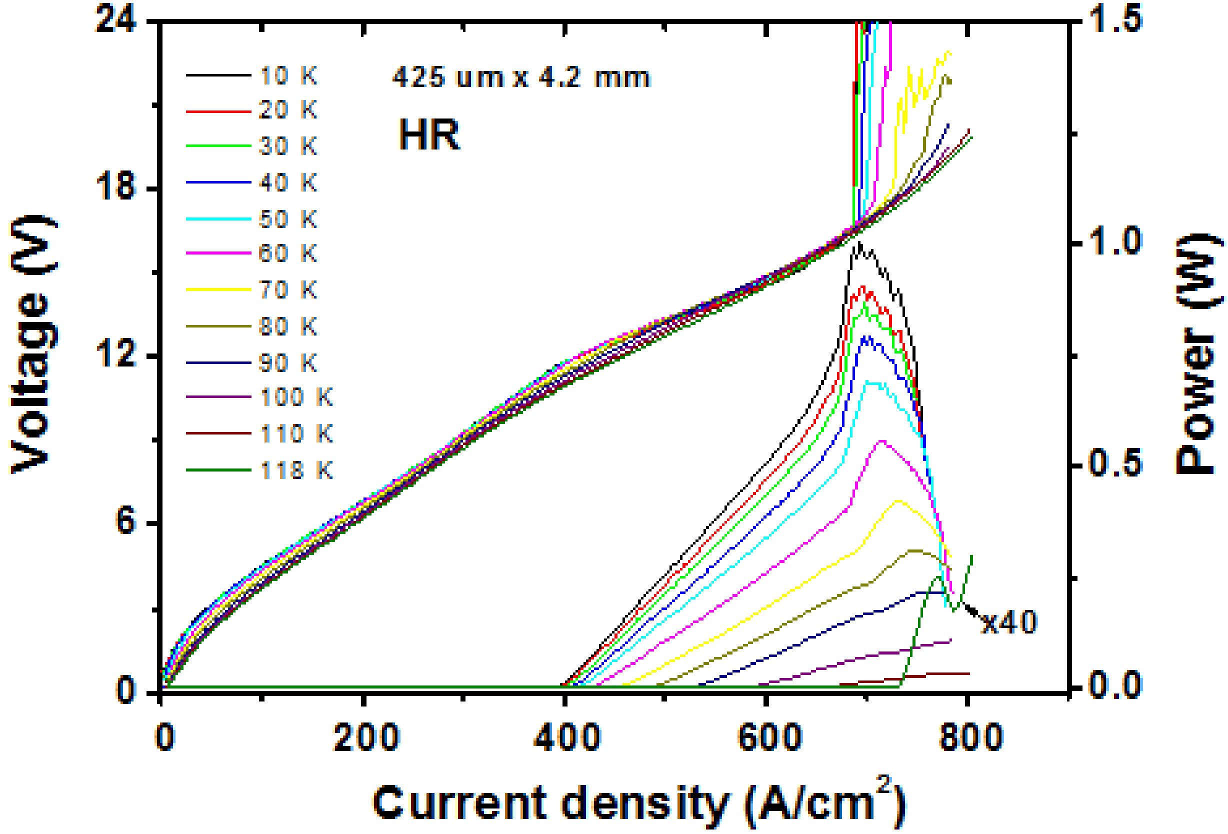

4.2 mm x 425 µm, facet coated; 10 kHz repetition rate; 2% duty cycle;

Lasing up to 1.01 W (peak) at ~ 3.4 THz; > 400 µW at 77 K, T_{max} = 118 K.

L. Li *et al*, *Electronics Letters* 50, 309 (2014).

Lowering the dissipated power

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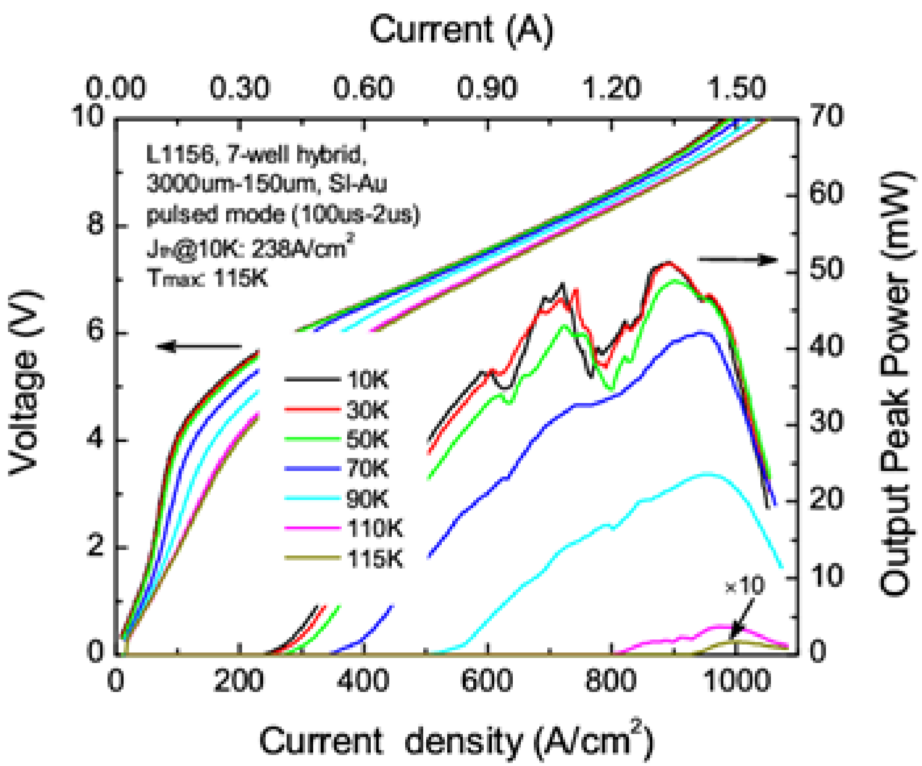

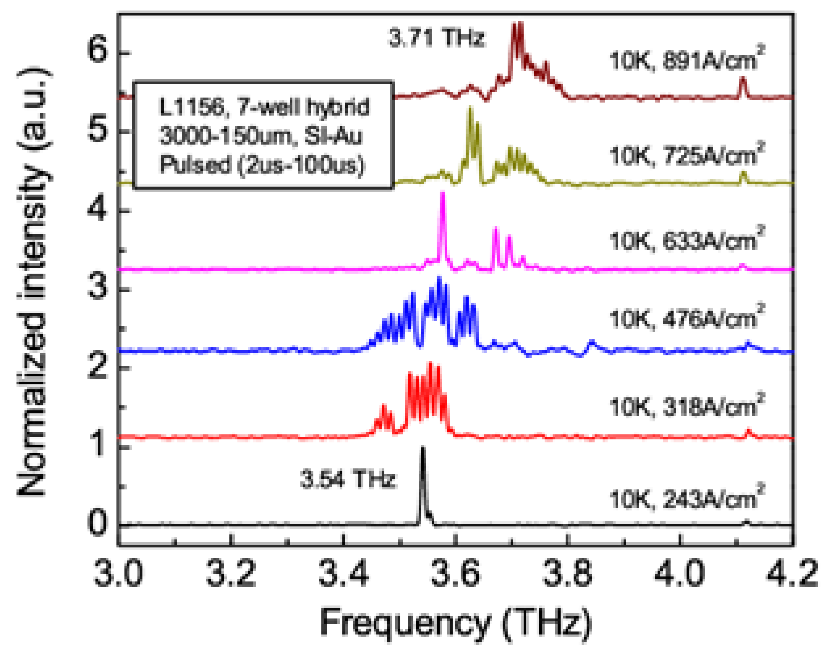

Layers: 7-well hybrid design for 3.5 THz

Device dimensions: 3000μm × 150μm × 15μm

- The frequency is **3.71 THz**, and the maximum pulsed lasing temperature is **115K**.
- The maximum output peak power at 10K is **51.35 mW**.

The good news…

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- 1 W peak power is possible, and 10s of mW continuous-wave power;
- QCLs have an intrinsically narrow linewidth (<20 kHz);
- Precise frequencies can be defined using periodic gratings defined into the ridge waveguides – DFB, second-order, and third order gratings;
- Operation has been demonstrated over the 1 – 5 THz frequency range;
- Heterodyne detection has been demonstrated;
- Ultrafast control is being implemented, and mode-locking shown;
- Radiation hardness has been demonstrated;
- The precise input power can be tailored, for a specific QCL wafer, to the application by changing the device dimensions.

But there are plenty of challenges…

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- High operation temperature is difficult owing to the small spacing between the lasing levels (cf k_BT) – this leads to thermal back-filling/parallel channels for electrons.

But, there is no fundamental physical limit in this *active* device

- The current maximum operating temperature is 199.5 K ***in pulsed mode*** (in the absence of a magnetic field);

- There are high dissipated electrical powers (with wall-plug efficiencies often < 1%), which is especially problematic when working continuous-wave at elevated temperatures;

- Operation is better at lower temperatures (ideally <20 K), whereas cryo-free coolers operate better at higher temperatures;

- QCLs are currently integrated into instrumentation using free-space coupling.

Low Cost Upper Atmosphere Sounder

QCL Plans

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Through the LOCUS team, and funding from NERC and CEOI, we will:

- Design QCLs with targeted frequencies for gas sensing in the upper atmosphere;
- Integrate, with RAL Space, QCLs into mixer blocks;
- Demonstrate optimised heat extraction, (hopefully) improving continuous-wave QCL performance to match the available space-qualified cryocooler performance;
- Demonstrate an integrated component technology suitable for atmospheric sensing and space applications.

See:

'Instrumentation for 1–5 THz Heterodyne Sounders' – Brian Ellison (RAL)

But, there will also be spin off benefits

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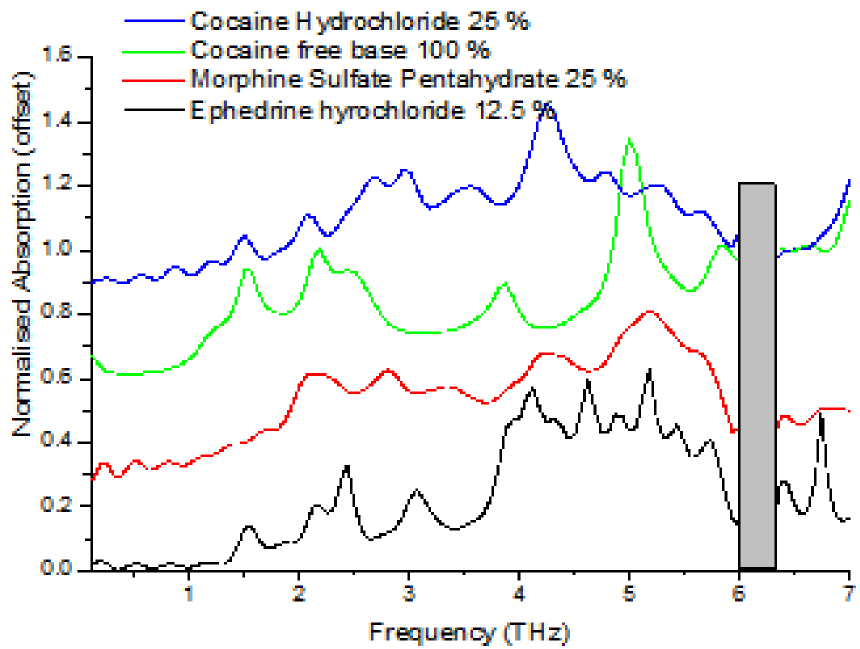

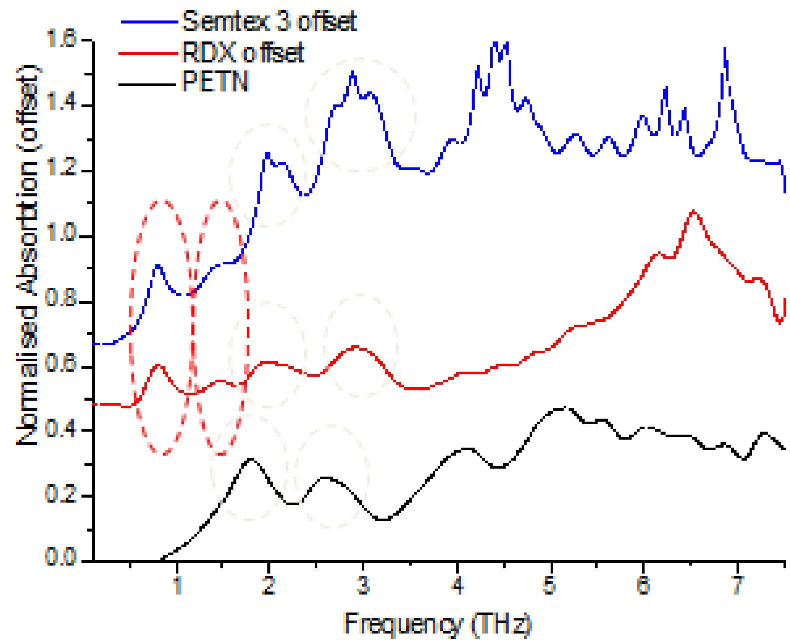

Clear spectral discrimination in THz frequency range, but compact instrumentation would open up many ground-based opportunities.

W. Fan *et al*, *Applied Spectroscopy* 61, 638 (2007);
A.G. Davies *et al*, *Materials Today* 11, 18 (2008);
A. D. Burnett *et al*, *Analyst* 134, 1659 (2009).