High power THz QCLs with output power over 1 W

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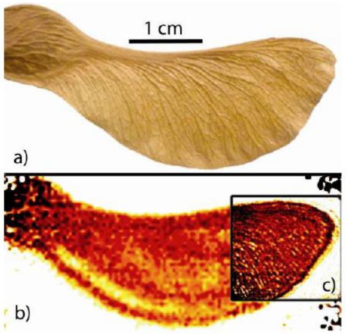
Outline

1. **Introduction**
2. **What can we do to achieve the high output power?**
   - Material quality
   - Active region design
   - Injector doping in the active region
   - Laser device geometry
   - Mirror loss
3. **High power QCL Results**
   - > 1W @3.4 THz
4. **Conclusions**

Why high power THz QCLs?



THz Applications

- Chemical and biological spectroscopy

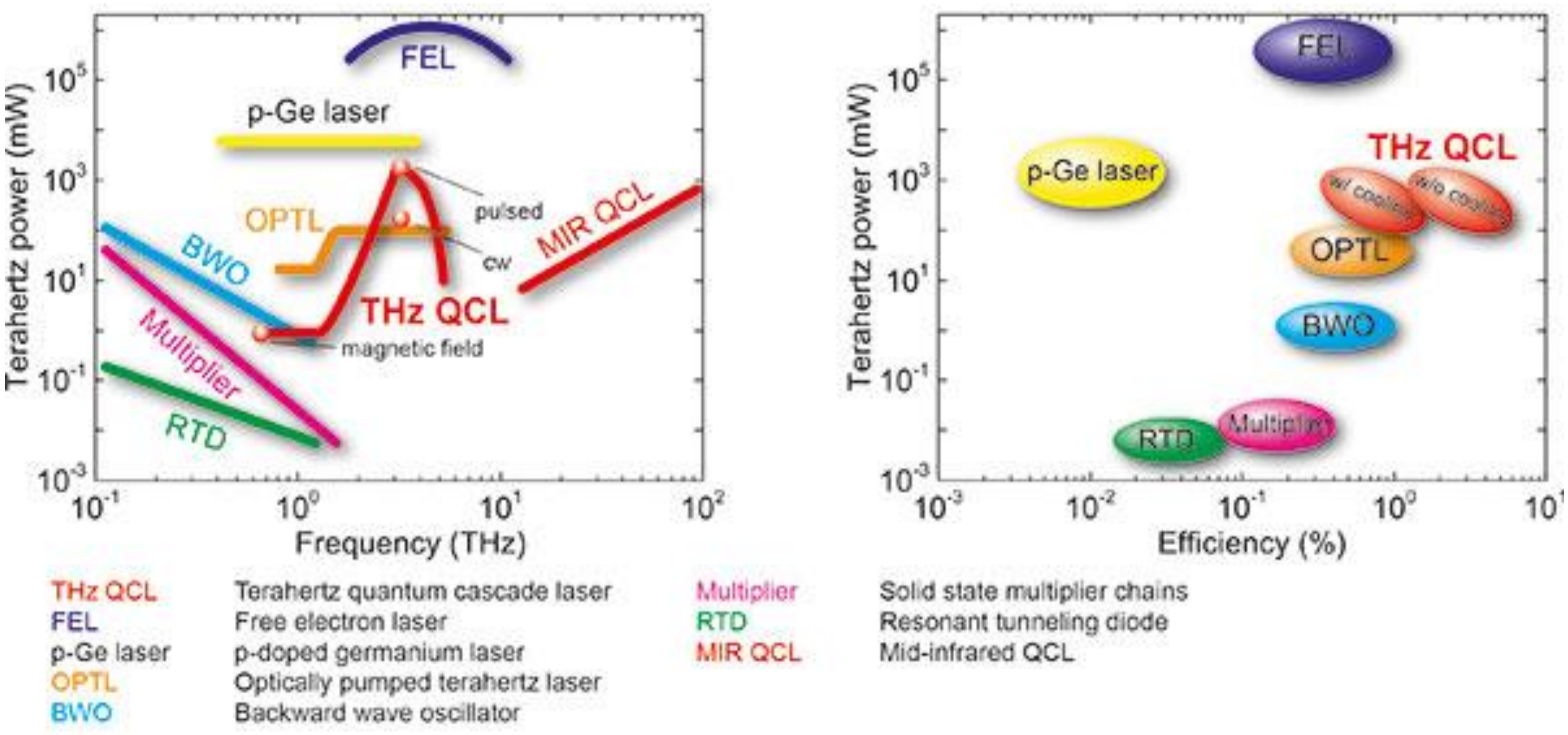
  Terahertz photon energy corresponds to rotational/vibrational energy levels in molecules

  For example, OH at 2.510 THz and 2.514 THz

- THz imaging (biological, medical, security applications)
- Telecommunication
- Local oscillator for heterodyne THz detection (astronomy and space)
- Nondestructive Evaluation of Air and Space Craft

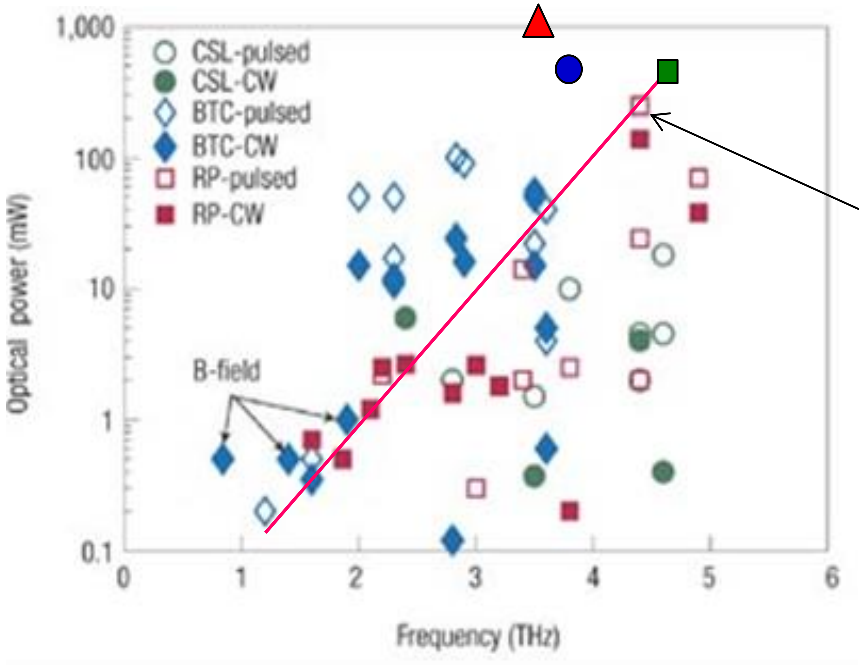
Remote sensing and imaging applications → high power is desirable!

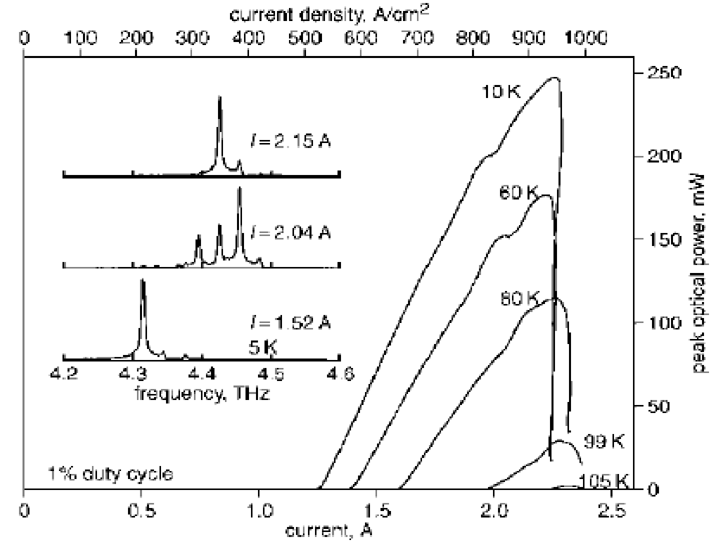
High power THz sources



The lack of any practical source of radiation has held back deployment of terahertz imaging.
FELs : powers up to several kW, but they must be housed in large-scale facilities.
p-Ge laser: power up to 10 W, but requires liquid helium cooling and a magnetic field
But every one of these classes of laser is impractical on account of its size, and this is hampering the large scale implementation of terahertz imaging.

High power THz QCLs: STATE-of-THE-ART





Q. Hu, MIT, *Electronics Letters*, 2006

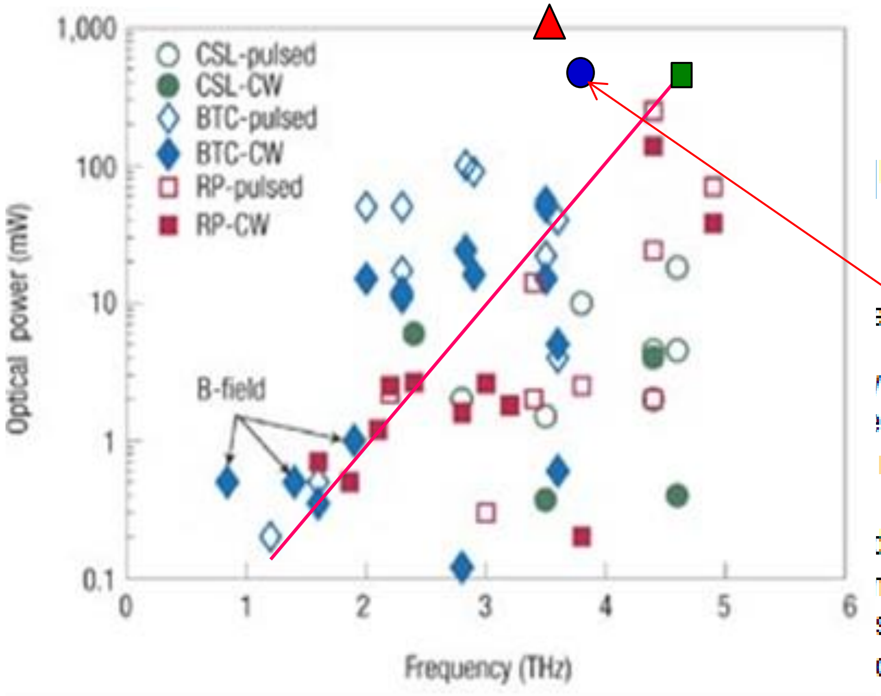
Main Performances @10 K

- Peak power=248 mW (pulsed); Frequency = 4.4 THz

Special Notes:

- Winston core used to enhance light collection

High power THz QCLs: STATE-of-THE-ART



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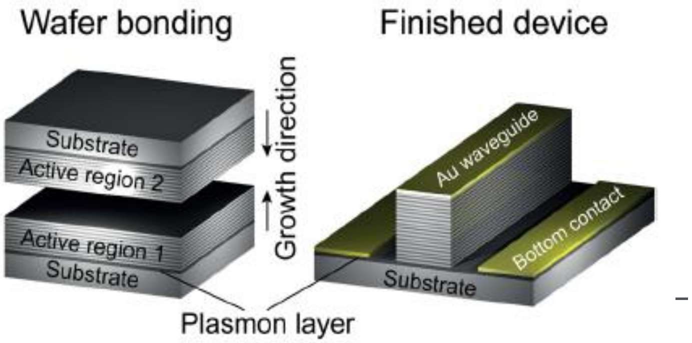
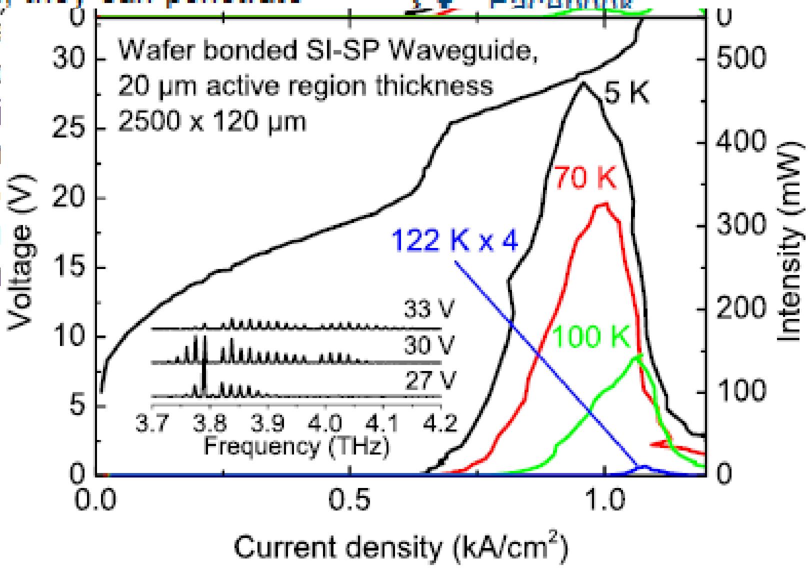


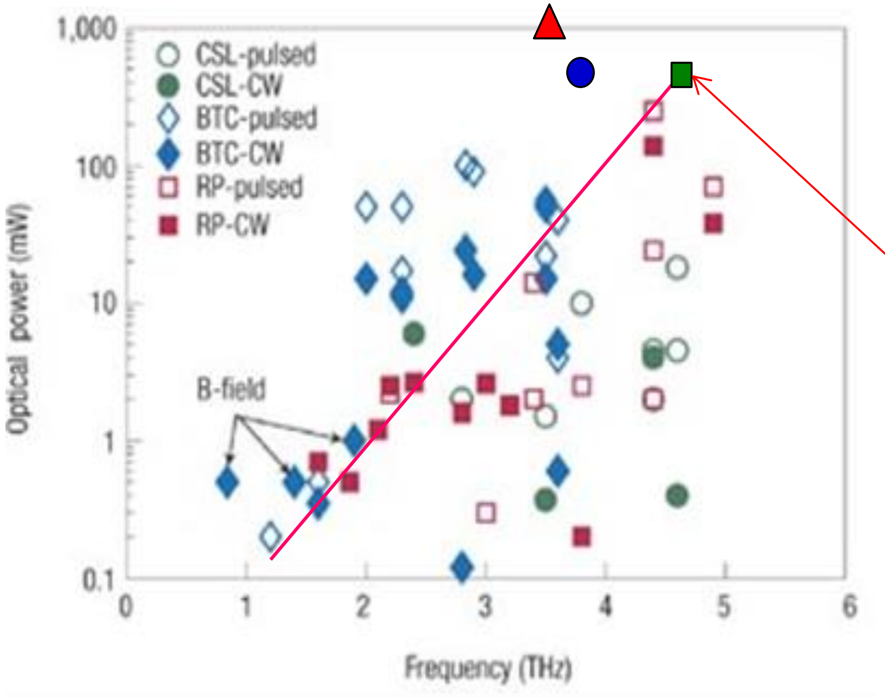


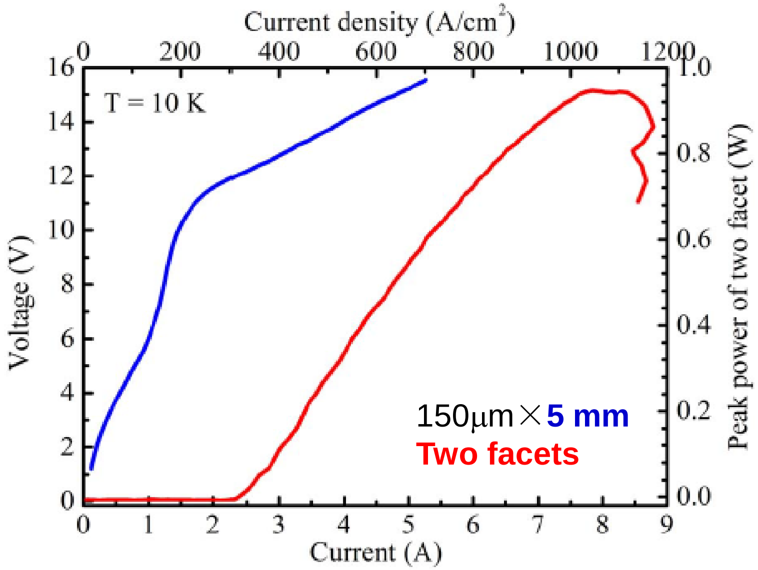
- **Wafer bonding structure symmetric QCLs**
- **Detector mounted in the cryostat**
- **5 K peak powers:**

---- 470 mW@3.8 THz (single facet, TU Vienna)

M. Brandstetter *et. al.*, **TU Vienna**, APL, 2013

High power THz QCLs: STATE-of-THE-ART

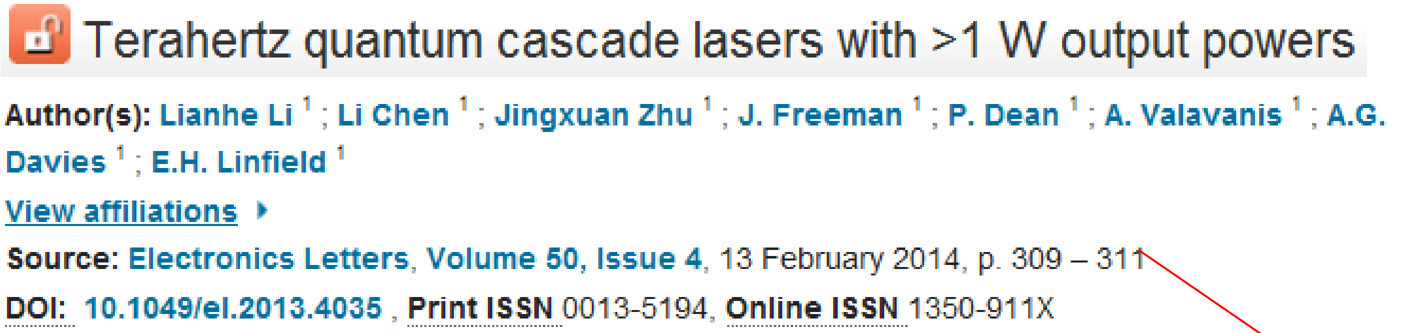




Faist *et.al.*, **ETHZ**, IRMMW-THz 2013

- **10 K peak powers from both facets:**
  ---- 437.5 mW@ 4.8 THz (one facet ,ETHZ)
  ---- 875.0 mW@ 4.8 THz (two facet ,ETHZ)

High power THz QCLs: STATE-of-THE-ART



Terahertz quantum cascade lasers with >1 W output powers

Author(s): Lianhe Li [1] ; Li Chen [1] ; Jingxuan Zhu [1] ; J. Freeman [1] ; P. Dean [1] ; A. Valavanis [1] ; A.G. Davies [1] ; E.H. Linfield [1]

View affiliations ▸

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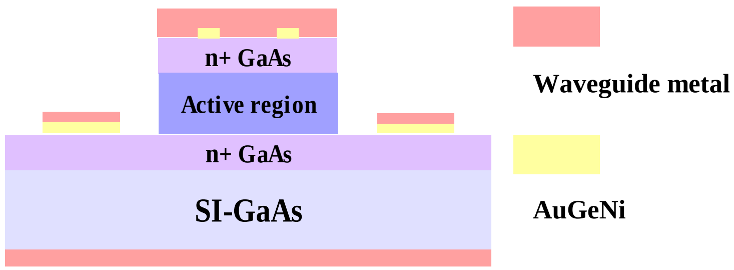
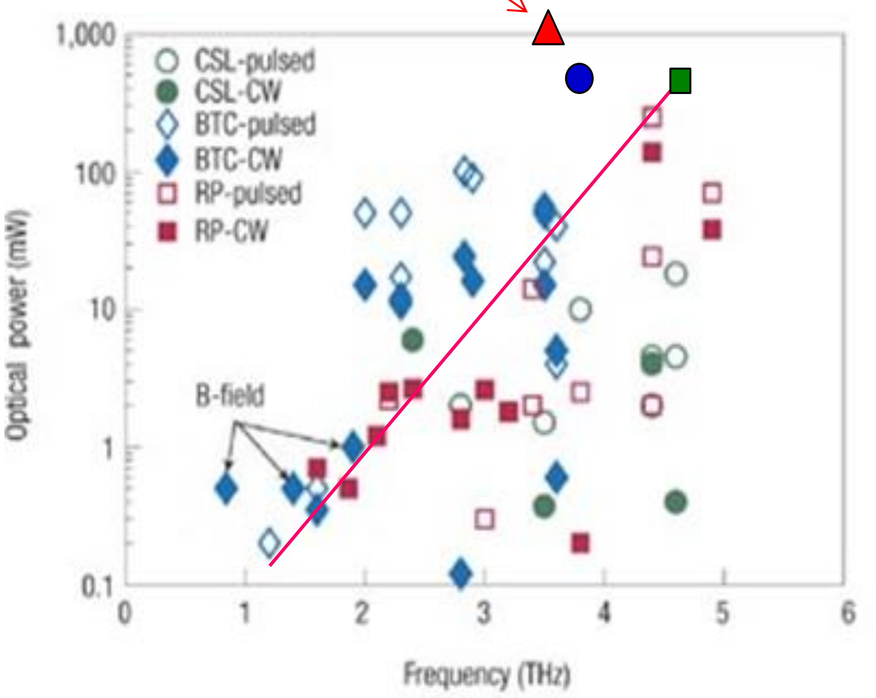


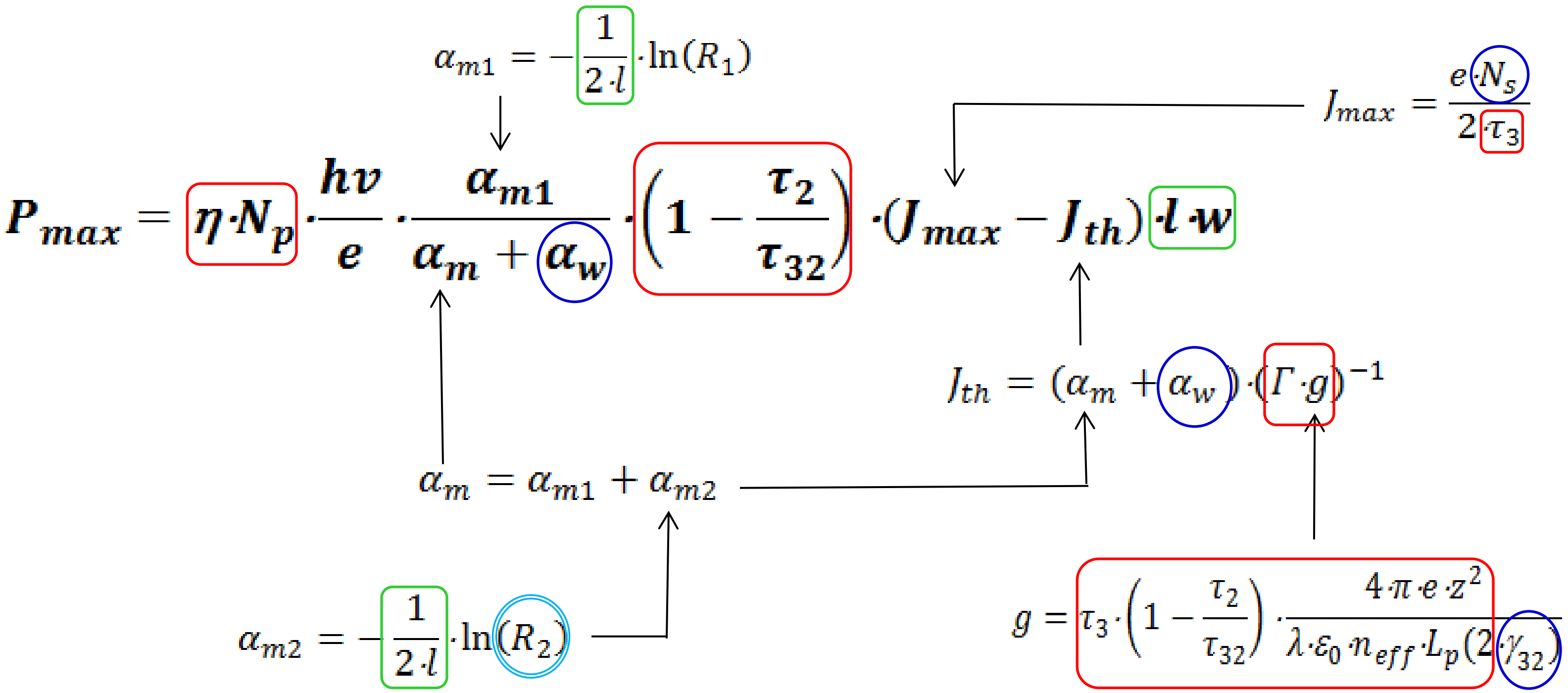
- Single surface plasmon waveguide
- Pulsed mode (100 μs, 2% duty cycle)
- One facet output power only



Factors enabling high QCL output power

1. **Excellent active region design**
2. **High material quality**
3. **Appropriate injector doping in the active region**
4. **Fabricating/using broad area lasers**
5. **Reducing mirror loss**

QCL output power: basic knowledge



$$\alpha_{m1} = -\boxed{\frac{1}{2\cdot l}}\cdot\ln(R_1)$$

$$J_{max} = \frac{e\cdot\enclose{circle}{N_s}}{2\cdot\boxed{\tau_3}}$$

$$P_{max} = \boxed{\eta\cdot N_p}\cdot\frac{h\nu}{e}\cdot\frac{\alpha_{m1}}{\alpha_m+\enclose{circle}{\alpha_w}}\cdot\boxed{\left(1-\frac{\tau_2}{\tau_{32}}\right)}\cdot\left(J_{max}-J_{th}\right)\boxed{l\cdot w}$$

$$J_{th} = \left(\alpha_m+\enclose{circle}{\alpha_w}\right)\cdot\left(\boxed{\Gamma\cdot g}\right)^{-1}$$

$$\alpha_m = \alpha_{m1}+\alpha_{m2}$$

$$\alpha_{m2} = -\boxed{\frac{1}{2\cdot l}}\cdot\ln\enclose{circle}{(R_2)}$$

$$g = \boxed{\tau_3\cdot\left(1-\frac{\tau_2}{\tau_{32}}\right)\cdot\frac{4\cdot\pi\cdot e\cdot z^2}{\lambda\cdot\varepsilon_0\cdot n_{eff}\cdot L_p\left(2\enclose{circle}{\gamma_{32}}\right)}}$$

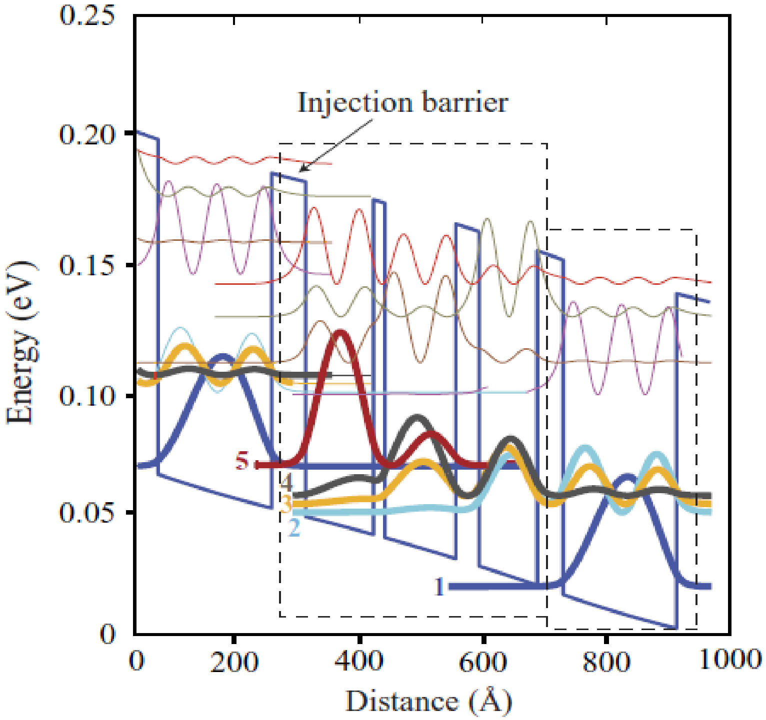
1. Active region design: η, N_p, τ_2, τ_{32}, Γ, τ_3, z, λ, L_p
2. Injector doping in the active region: N_s, α_w, γ_{32}
3. Laser device geometry : l and w
4. Mirror loss: R_2

QCL active region design

New Journal of Physics
The open-access journal for physics

Bound-to-continuum terahertz quantum cascade laser with a single-quantum-well phonon extraction/injection stage

Maria I Amanti[1], Giacomo Scalari[1], Romain Terazzi[1],
Milan Fischer[1], Mattias Beck[1], Jérôme Faist[1,3], Alok Rudra[2],
Pascal Gallo[2] and Eli Kapon[2]



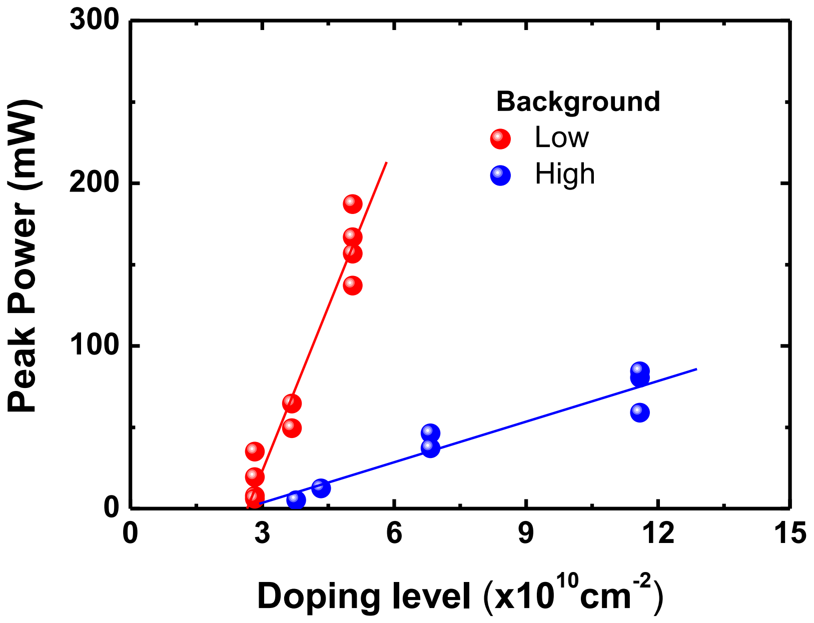
Active Region Design:

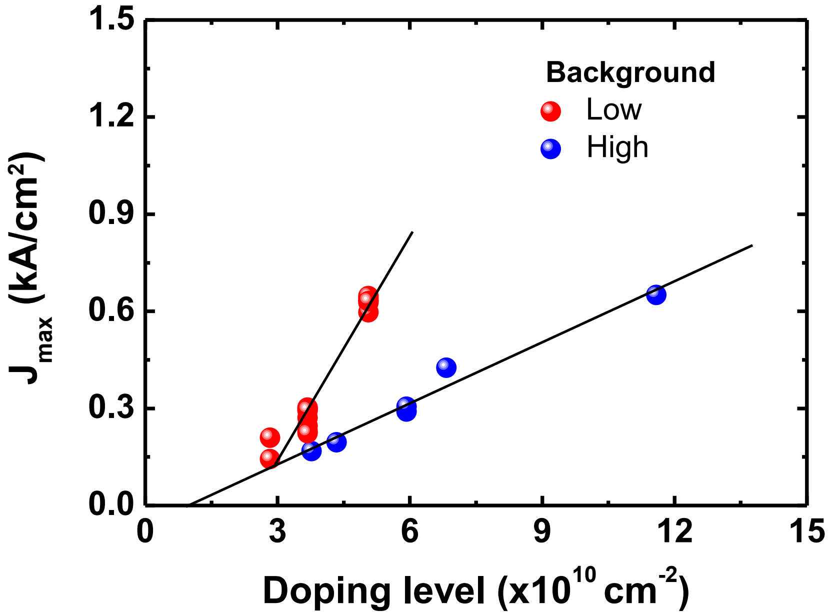
Original $\mathrm{Al_{0.15}Ga_{0.85}As/GaAs}$
55/110/**18**/115/**38**/94/**42**/184

Modified $\mathrm{Al_{0.16}Ga_{0.84}As/GaAs}$
52/103/**17**/107.5/**36**/88/**39.5**/172

NB: Starting from the injector barrier.

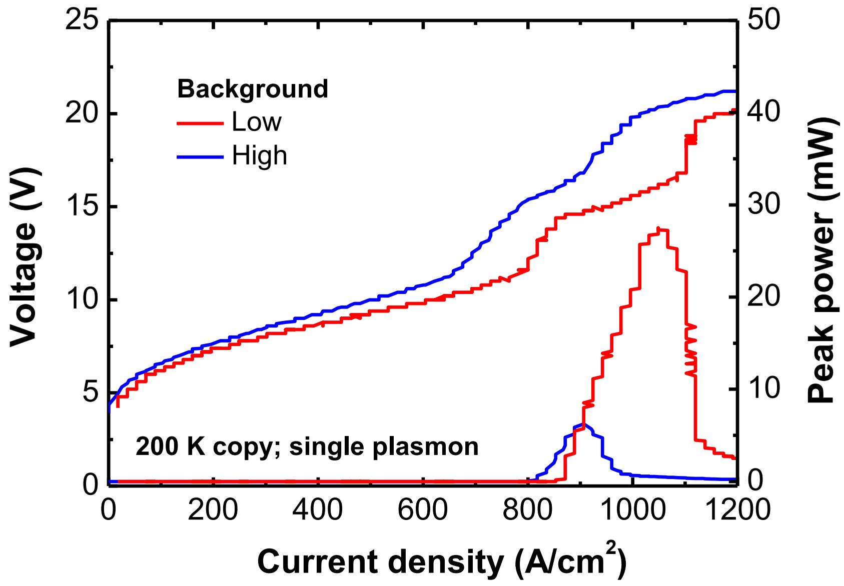
Impacts of injector doping level

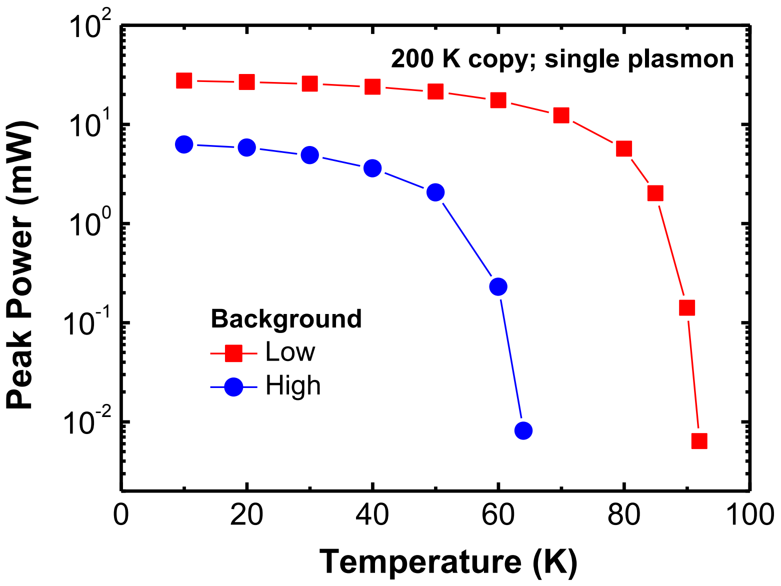




- Same QCL active design, different background and injector doping
- Dynamic range and output power scale with injector doping

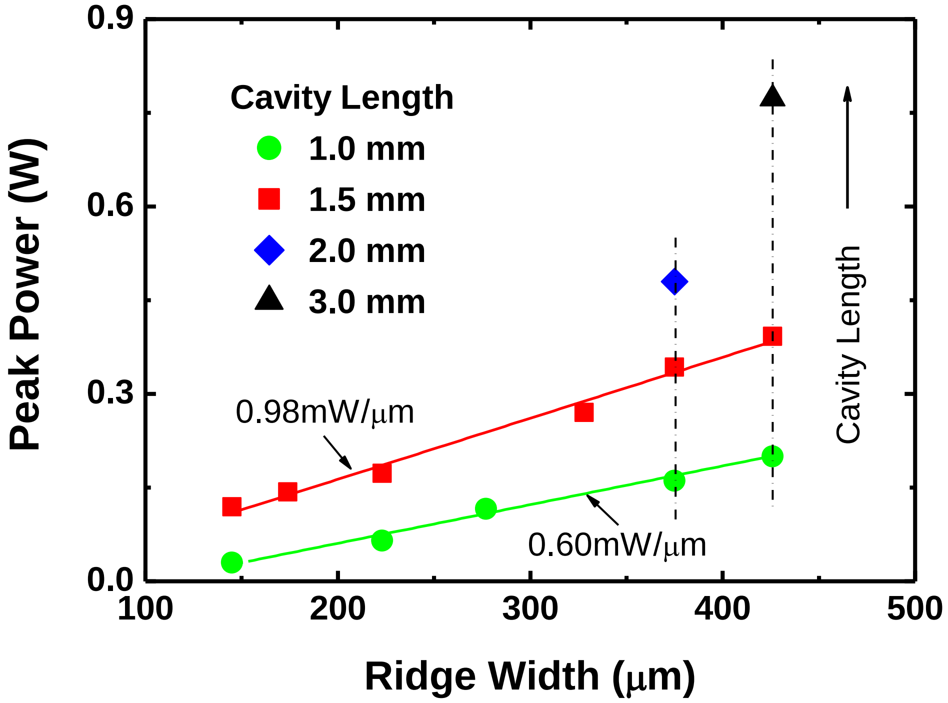
Material quality: background doping





- Same QCL active design and injector doping level
- Different background (P-type, grown by two Ga cells but same Al cell)
- Lower background → Larger dynamic range and higher output power
- > $2 \times 10^{+15}$ cm^{-3}, devices are rarely lasing

Impacts of QCL device geometry: l and w



$$\alpha_m = -\frac{1}{2 \cdot l} \cdot \ln(R_1 \cdot R_2)$$

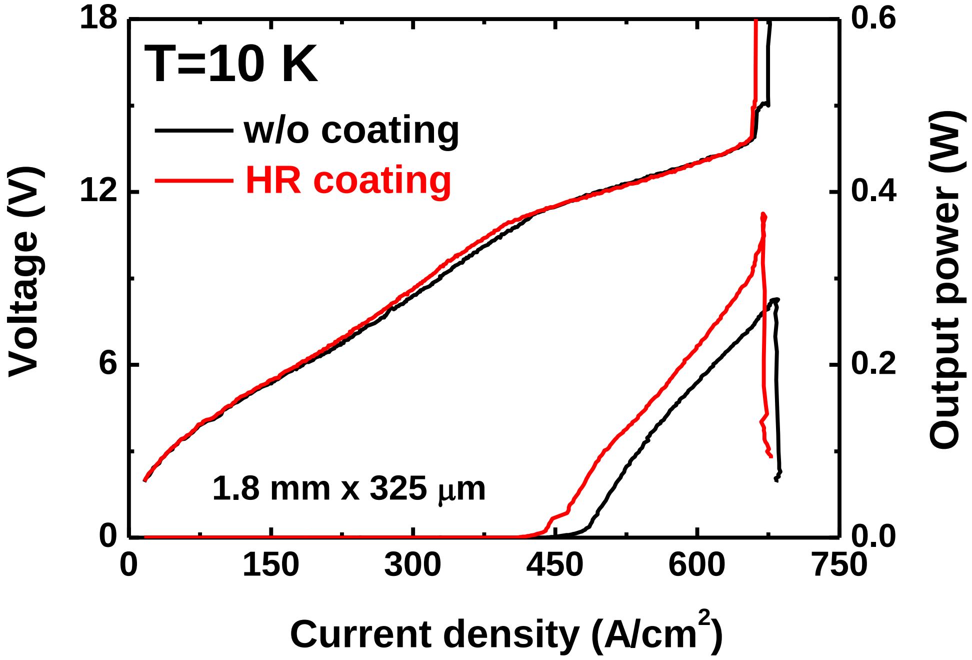
$$J_{th} = (\alpha_m + \alpha_w) \cdot (\Gamma \cdot g)^{-1}$$

$$\frac{dL}{dw} \propto \frac{J_{max} - J_{th}}{\alpha_m + \alpha_w}$$

- **Power scaling linearly with *l* and *w***
- **Scaling factor, *dL/dw*, increases with *l***
- **Max. peak power of 780 mW (single facet)**

Effects of facet coating

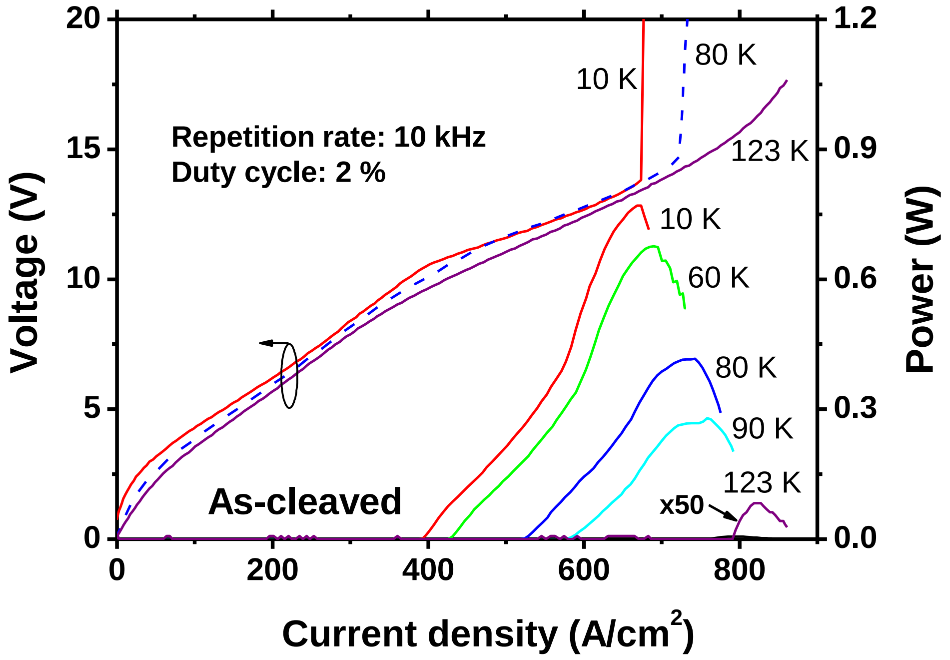
Electron beam of SiO_2(150 nm)/Ti(10 nm)/Au(150 nm)/SiO_2(200 nm)

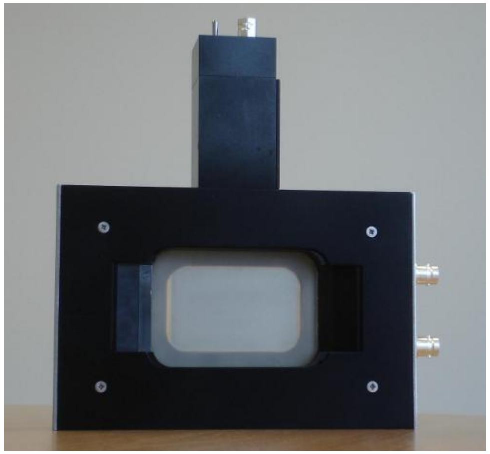


- Threshold current density decrease remarkably
- Peak power increase by 36 %, i.e., 375 mW *vs.* 275 mW

Typical LIVs of the high power Terahertz QCL

Pulsed operation, 425 μm wide, 3 mm long, as-cleaved





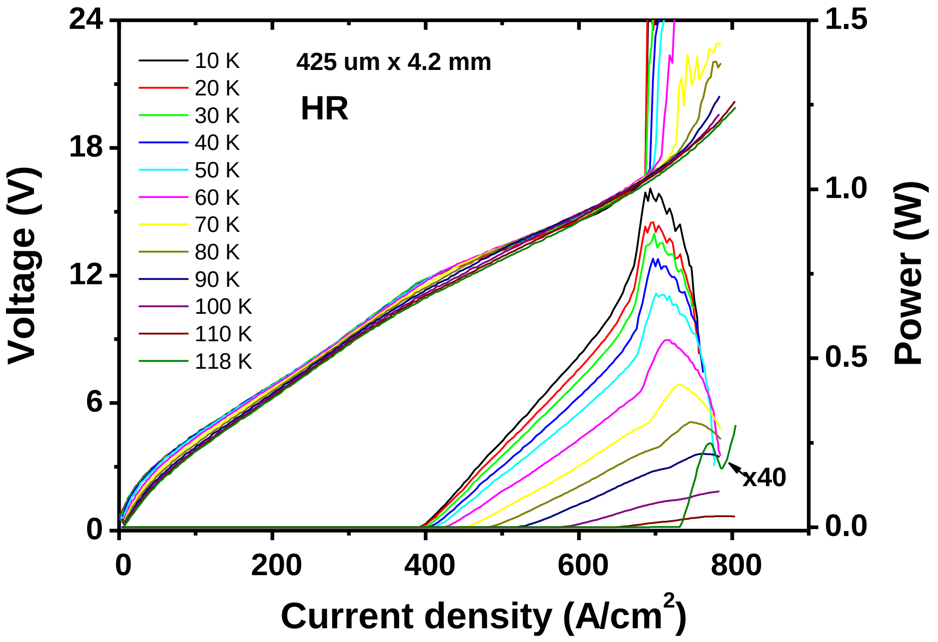
Power Meter: Thomas Keating

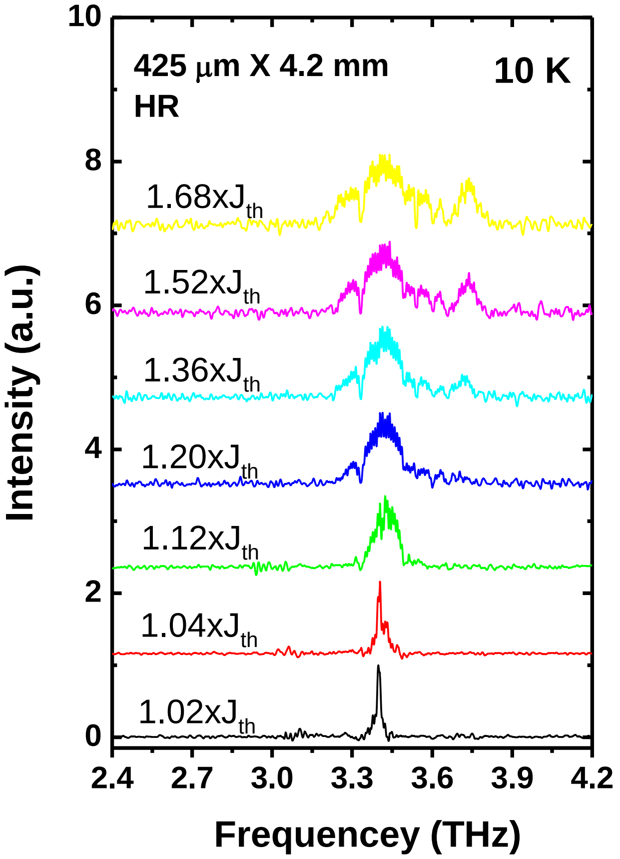
- **3.5 cm separation**
- **Neither Winston core nor light pipe used**
- **No collect efficiency considered**

- **Single facet peak power of 780/420 mW at 10/77 K**
- **Wall-plug efficiency of 1.4% at 10K**
- **Differential quantum efficiency of ~ 31 photons/electron**

High power Terahertz QCLs at 3.4 THz

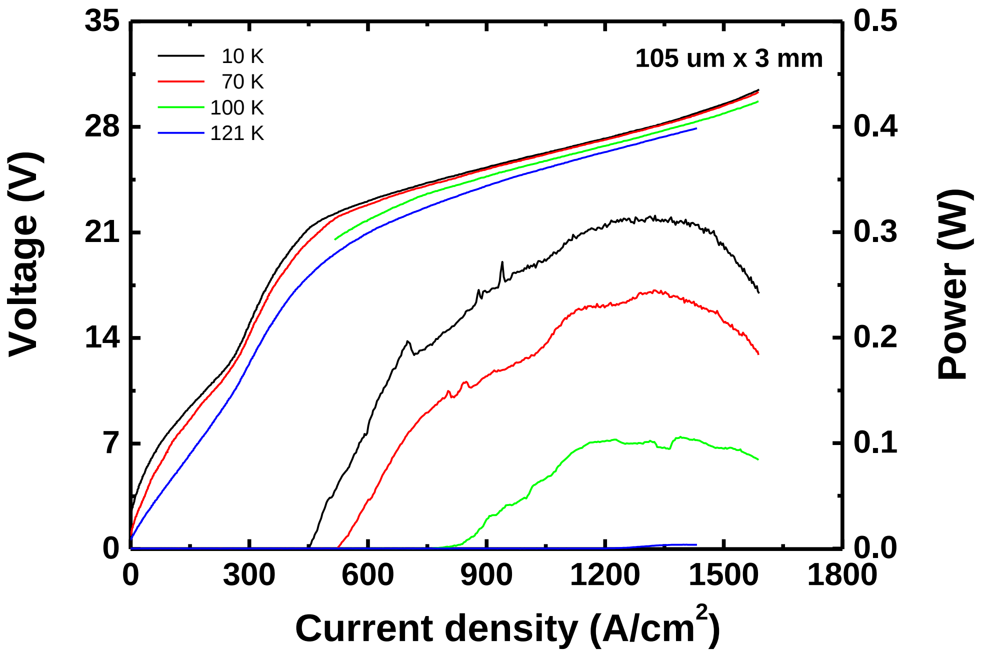
Pulsed operation, 425 μm wide, 4.2 mm long, with HR coating

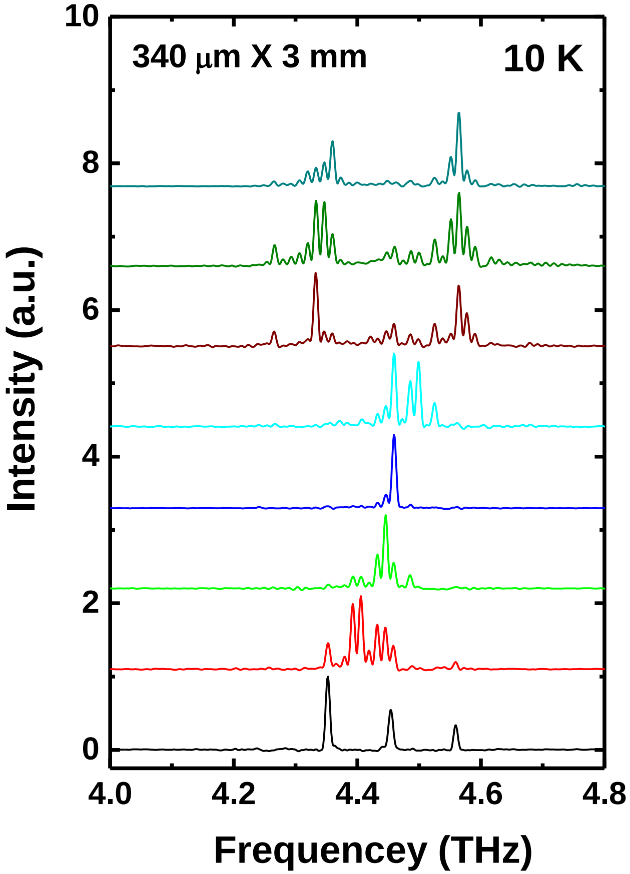




- **Peak output power of 1.01 W**
- **Lases up to 118 K**
- **Lasing around 3.4 THz**

High power Terahertz QCLs (Latest News)



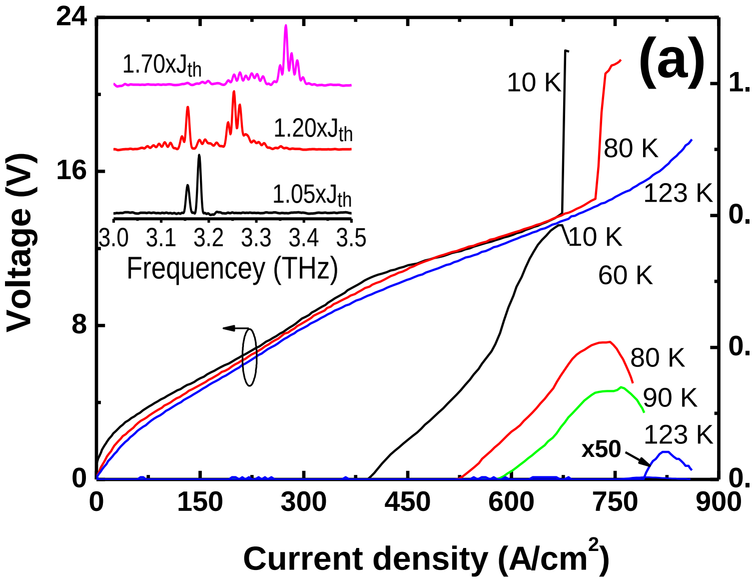


- Peak output power of 0.92 W
- Lases up to 121 K
- Lasing around 4.3-4.6 THz
- Emission from single facet

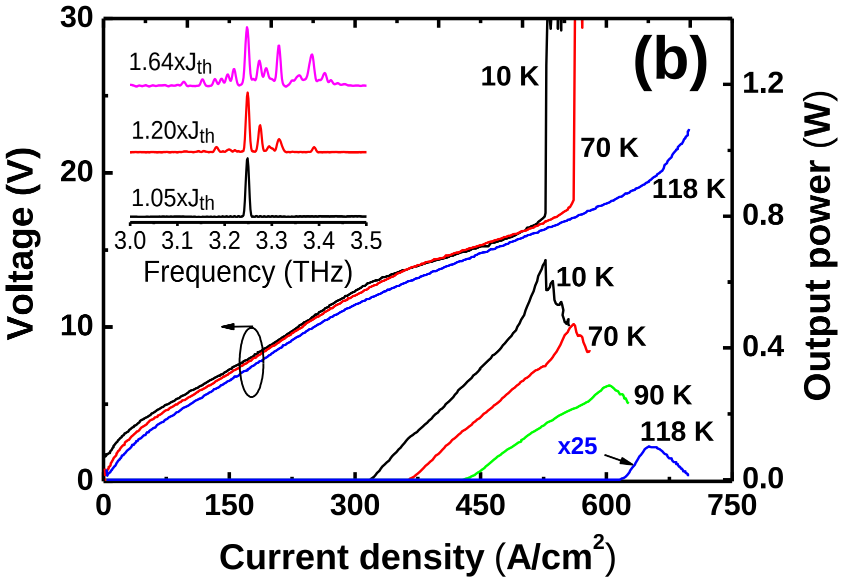
Growth Reproducibility

High power results are repeatable in different growth campaign.

Sample in 2013 growth campaign



Sample in 2014 growth campaign
(After MBE system refurbishment)



Pulsed operation, 425 μm wide, 4.2 mm long, without HR coating

- **Peak output power of 0.78 W**
- **Lases up to 123 K**
- **Lasing around 3.4 THz**

- **Peak output power of 0.67 W**
- **Lases up to 118 K**
- **Lasing around 3.3 THz**

Conclusions

1. **Factors enabling high QCL power were systematically investigated.**
2. **High power QCLs emitting around 3.4 THz were demonstrated.**
   - ➢ **At 10 K, peak power >1 W (first demonstration);**
   - ➢ **At 77 K, peak power of ~420 mW.**
3. **Growth reproducibility was confirmed.**

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