Hot electrons in THz quantum cascade lasers

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Outline

- Experimental evidence of hot-electron cooling associated with photon emission
- Energy balance equation model in QCLs→ correlation of laser induced hot electron cooling with quantum efficiency
- Assessment of:
  - Internal quantum efficiency
  - External differential efficiency
  - Wall-plug efficiency
  - Slope efficiency
  - Electron-lattice energy relaxation times

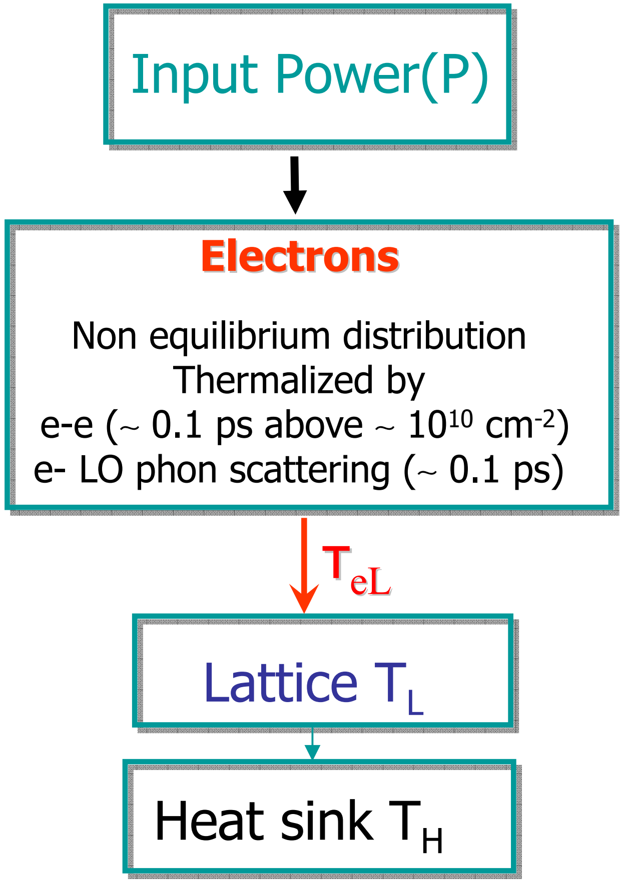
Motivation

- In **Electronic** and **Photonic** devices electrons release the excess energy gained from the applied electric field by:
    - exciting other electrons
    - emitting phonons or photons

- Equilibrium condition between ***P*** and the energy loss rate: average electron energies > crystal lattice one → **hot-electron populations**

- Electronic distributions: Fermi-Dirac functions characterized by temperatures $T_e >> T_L$

- Relevance of including hot-electron distributions in **semiconductor laser modelling** → hot electron effects are directly correlated with physical parameters central in the laser theory



Energy balance in QCLs

- Energy relaxation channels in QCL:

-Inter and intra-subband e-e scattering

$\tau_{ee} \propto \Delta E/n_j$ → scattering time is proportional to the energy separation between the initial and final states

-e - phonon scattering

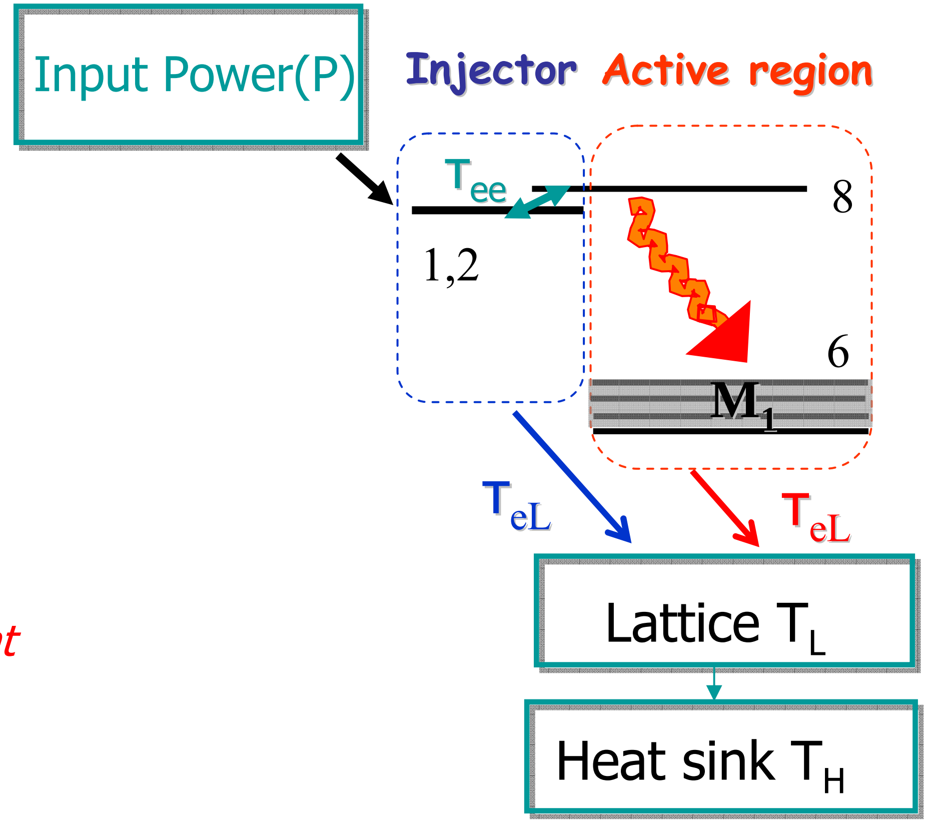
τ_{eL} energy loss lifetime between each electronic subsystem and the lattice

- e-impurity
-interface roughness

Interplay between above processes → different electron temperatures among subbands

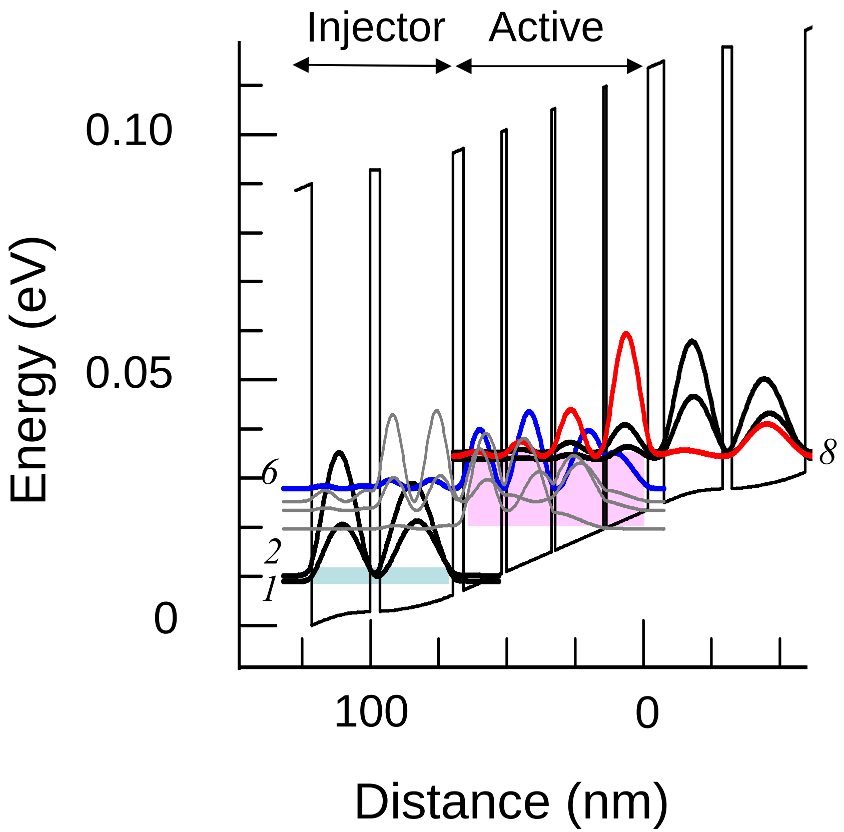
-QCL ideal to study hot electron populations:

- *Large P*
- *High thermal resistances*
- *Limited e-lattice relaxation efficiency*



Low frequency THz QCLs

Walther et al. APL 89, 231121



Quantum design:

- **Bound-to-continuum** scheme
- **Two-level injection/depletion module**
- E_{86} = 7.4 meV ; z_{86} = 10.1 nm
- $E_{1-2,8}$ ~ 0.6 meV

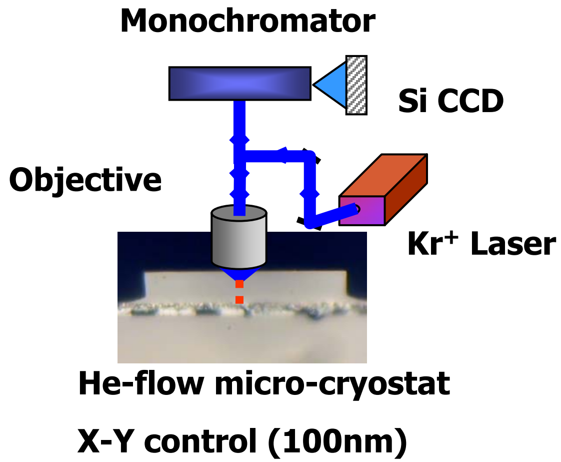
Two electronic subsystems can be identified:

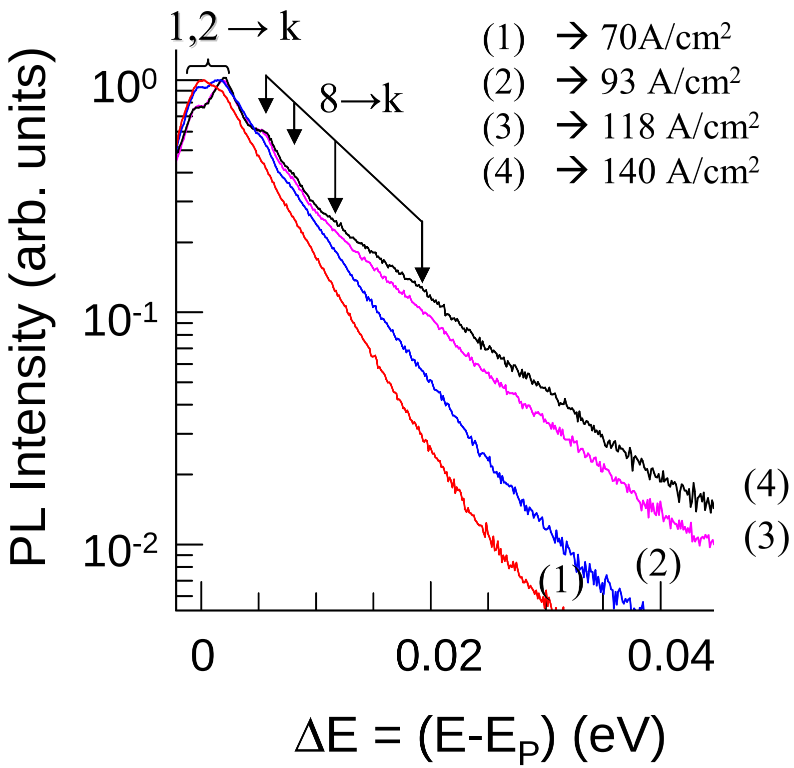
- **Active region**: includes the upper laser level and the depletion miniband.
- **The injector**: doublet of closely spaced lowest energy levels.

Experimental approach

- Photoluminescence spectroscopy on the laser front facets

- Extract local lattice and electronic temperatures from PL analysis

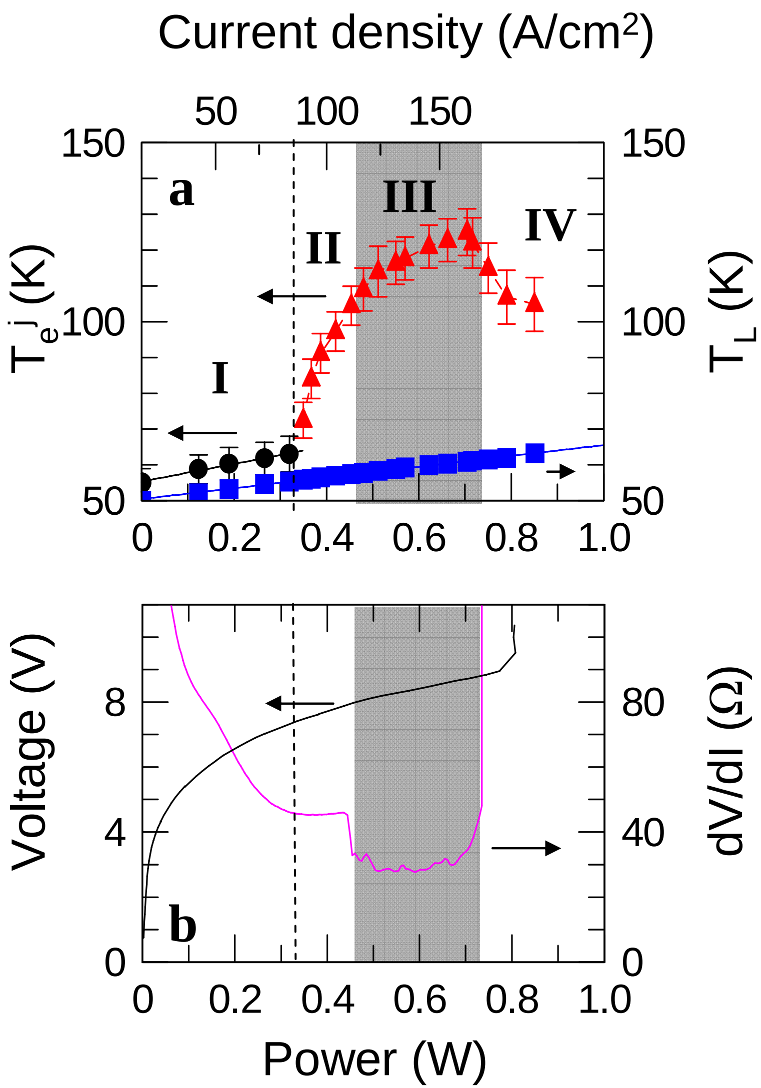




(1) → Low V; Below the threshold for carrier injection into the upper state → most of the electrons are sitting in the **injector doublet**

(**2**-**3**-**4**) → Higher V; the energy difference between the injector and the upper state is reduced → additional peaks on the high energy tail of the main PL bands shows that **electrons are injected into level 8**.

Electronic and Lattice temperatures

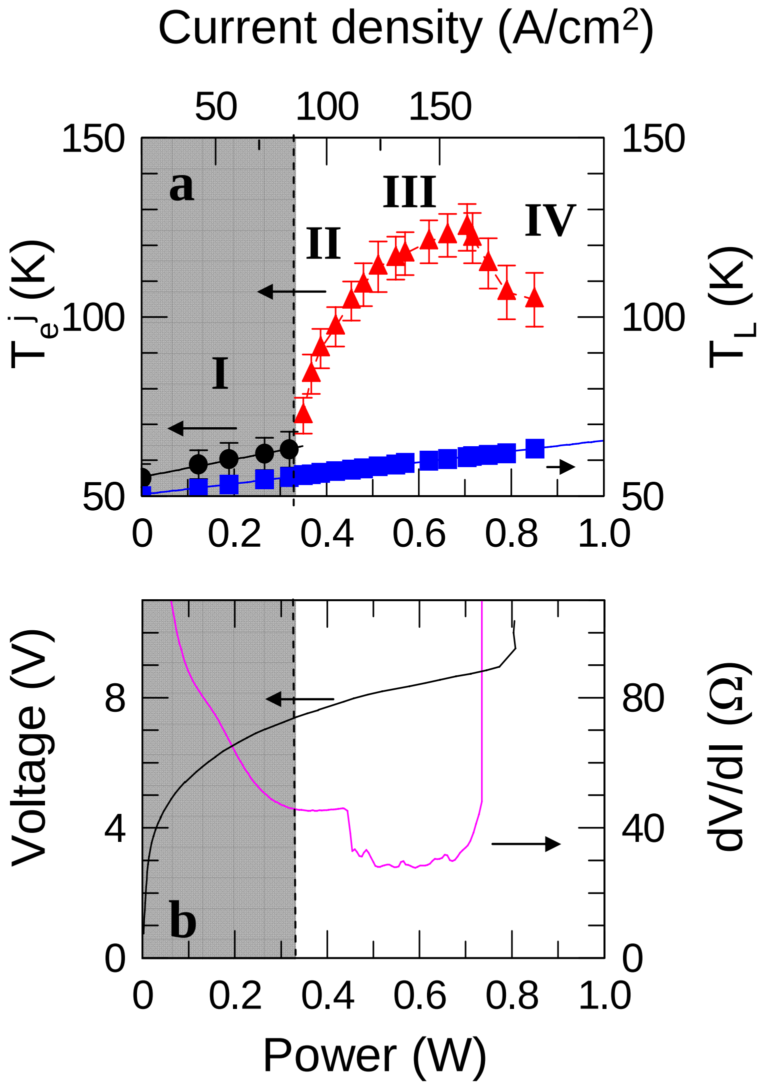


Measurement of the electron temperatures:

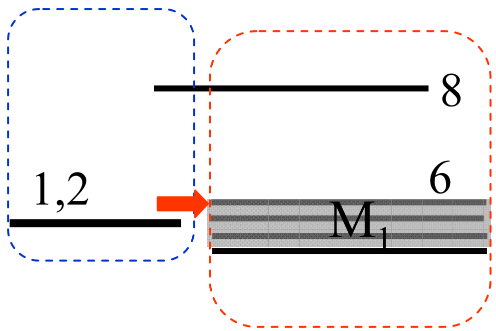
- Below threshold of alignment
- After injection into the upper state
- Above lasing threshold

Four regions, clearly correlated with features in the **transport measurements** can be identified.

Electronic and Lattice temperatures



Below injection into level 8



- Efficient ($\tau_{ee}\approx$100 fs) energy redistribution process between the injector and $M_1 \rightarrow T^e_{inj} \approx T^e_{active}$

- $$\frac{dE_j}{dt} = \overline{P} - \frac{n_j k}{\tau_{eL}}(T_j^e - T_L)$$

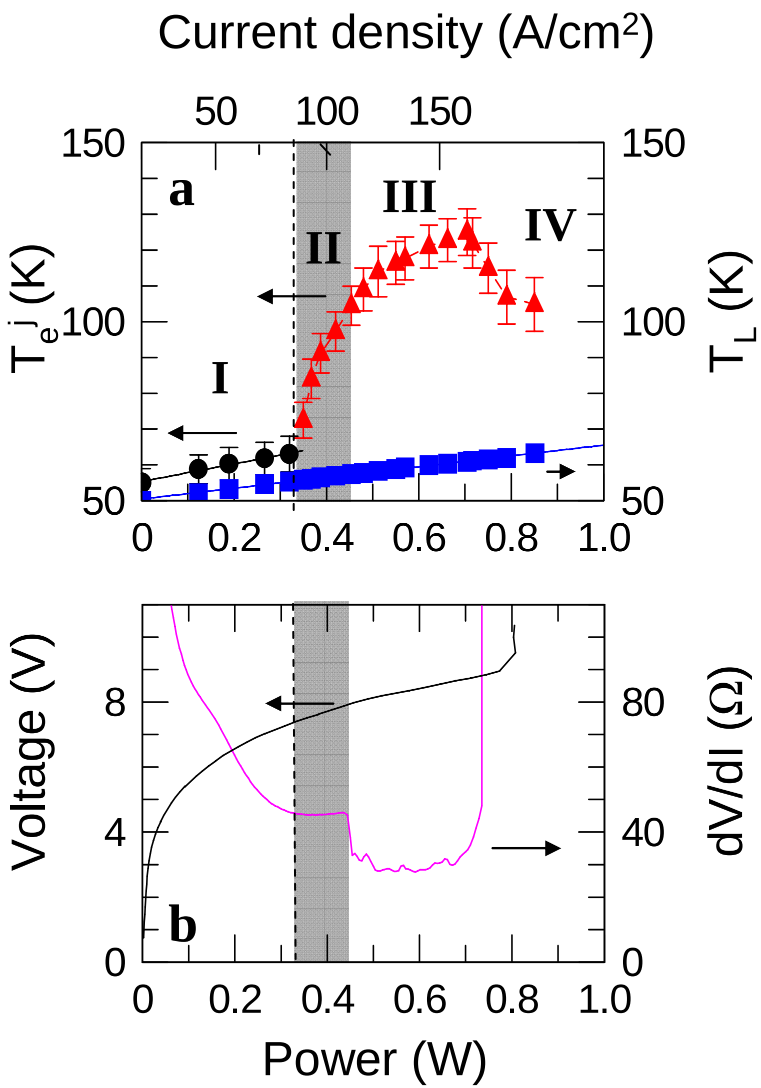
Experimental $$R_e = \frac{T^e_{inj}}{P} \approx R_L$$

→ Efficient **electron-lattice scattering**

Rate equation:

$$\tau_{eL} = [N_e N k_B (R_e - R_L)] = 0.22 - 0.25\,ps$$

Electronic and Lattice temperatures

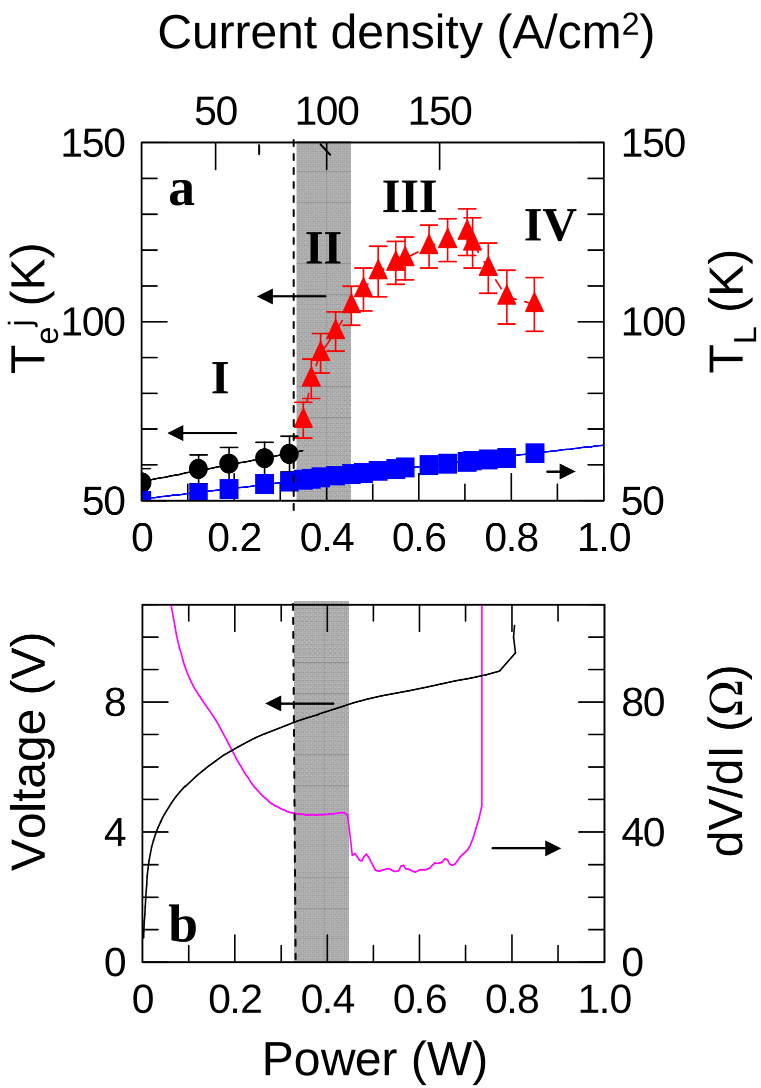


II Above alignment

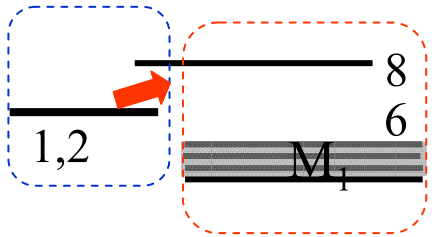
- The measured electronic temperature corresponds to T^e_{active}
  - Injection in level 8 → confirmed by new PL peaks
  - Subband populations in the same quantum wells equilibrate quickly (100-200 fs) to a common T_e
  - Experiments in BTC THz QCLs demonstrate that the miniband and the upper subband share a common T_e

Vitiello *et al. **APL** 89, 021111, (2006).*

Electronic and Lattice temperatures



II Above alignment

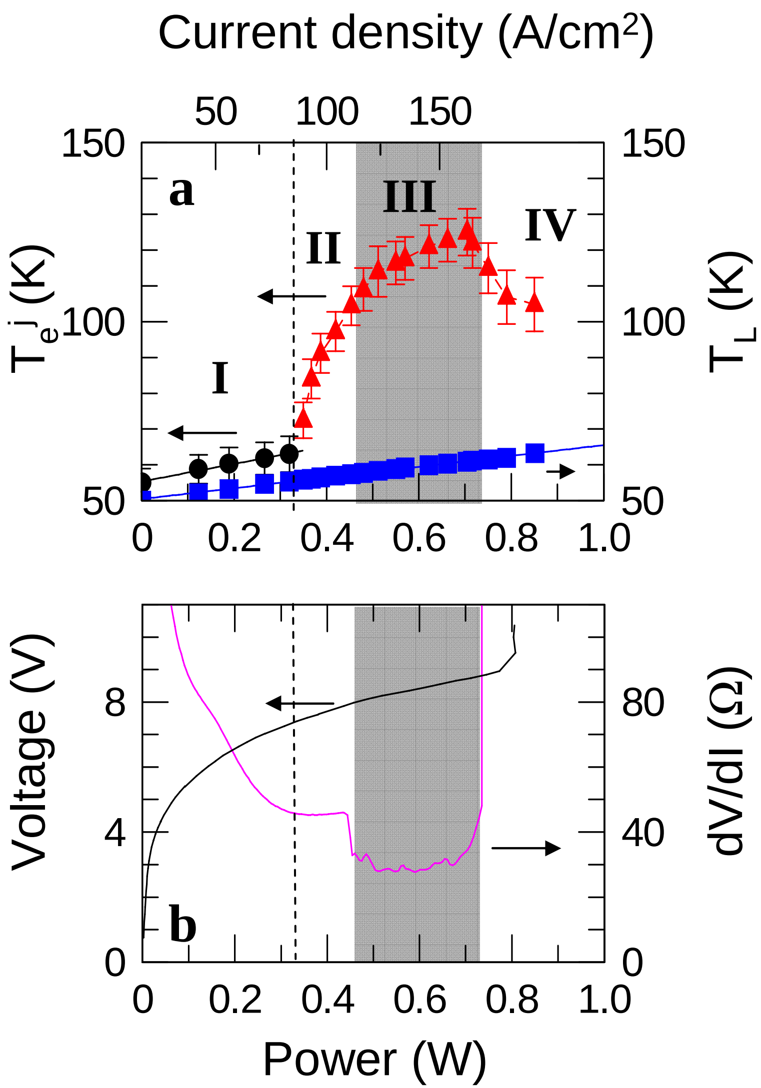


- Cold *electrons* progressively populate level *8*
- *electrons* are scattered elastically or quasi-elastically with a large excess energy to a lower state
- *electrons* thermalize within their respective subbands at a temperature $T^e_{active} > T^e_{inj}$

Heating of the upper laser level:

- A comparable amount of injected electrical power is distributed between the two subsystems
- But $n_{active} << n_{inj}$

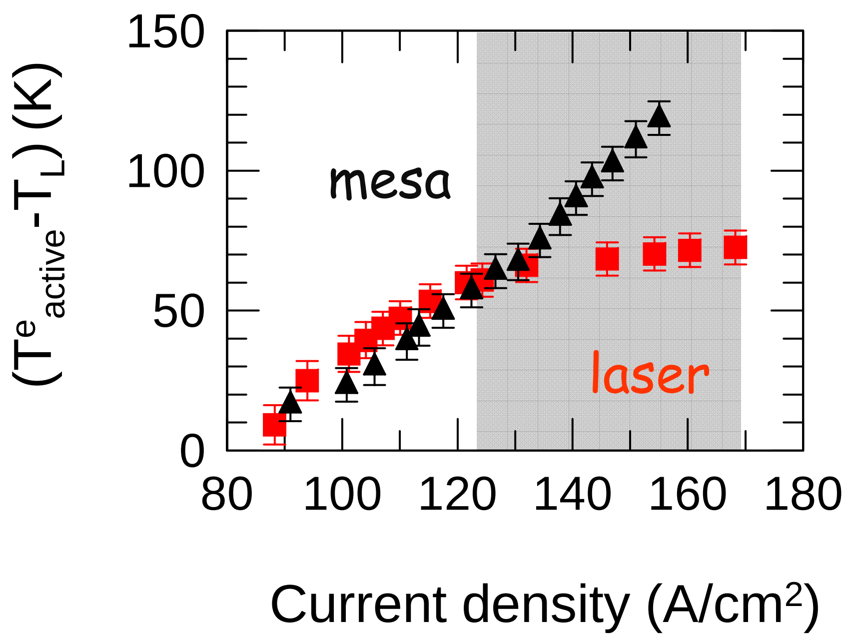
Electronic and Lattice temperatures



Lasing region

Efficient **hot electron cooling** by photon emission → Photon emission extracts part of the input power

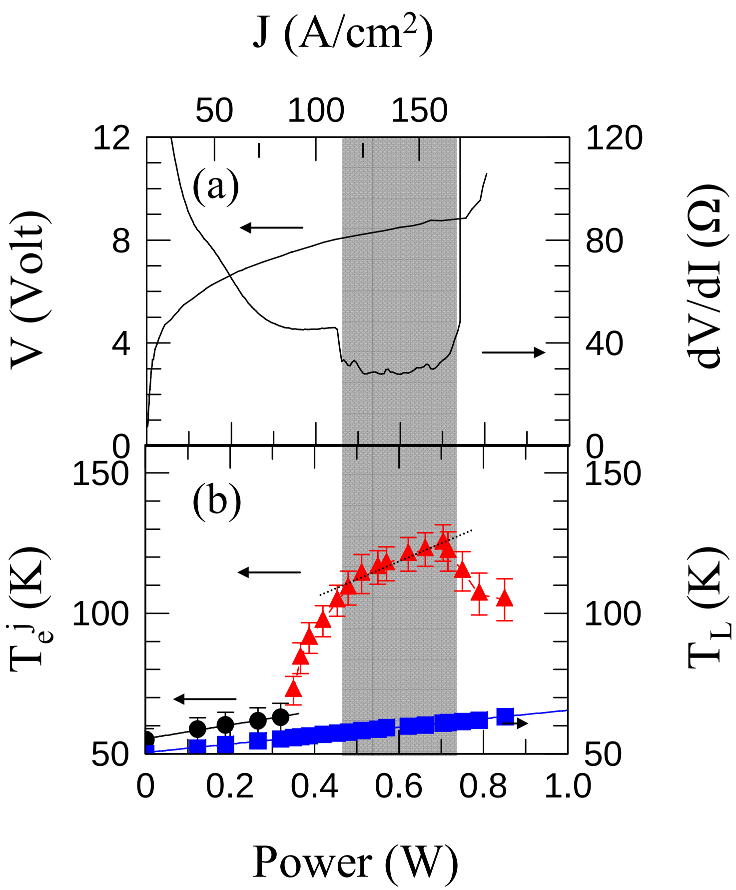
Further proof: Lasers vs mesas



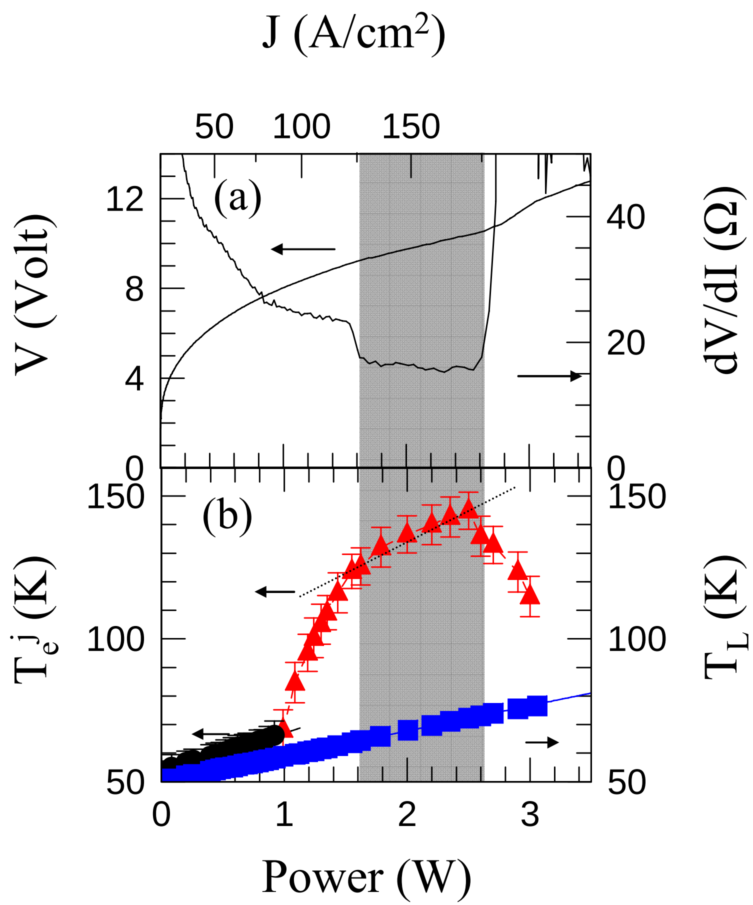
- Mesa device → No evidence of change in the slope $\frac{d\left(T_{active}{}^{e}-T_{L}\right)}{dJ}$
- Change in the slope $\frac{d\left(T_{active}{}^{e}-T_{L}\right)}{dJ}$ at the onset of lasing

Electronic and Lattice temperatures

Sample A (50 µm × 1mm)



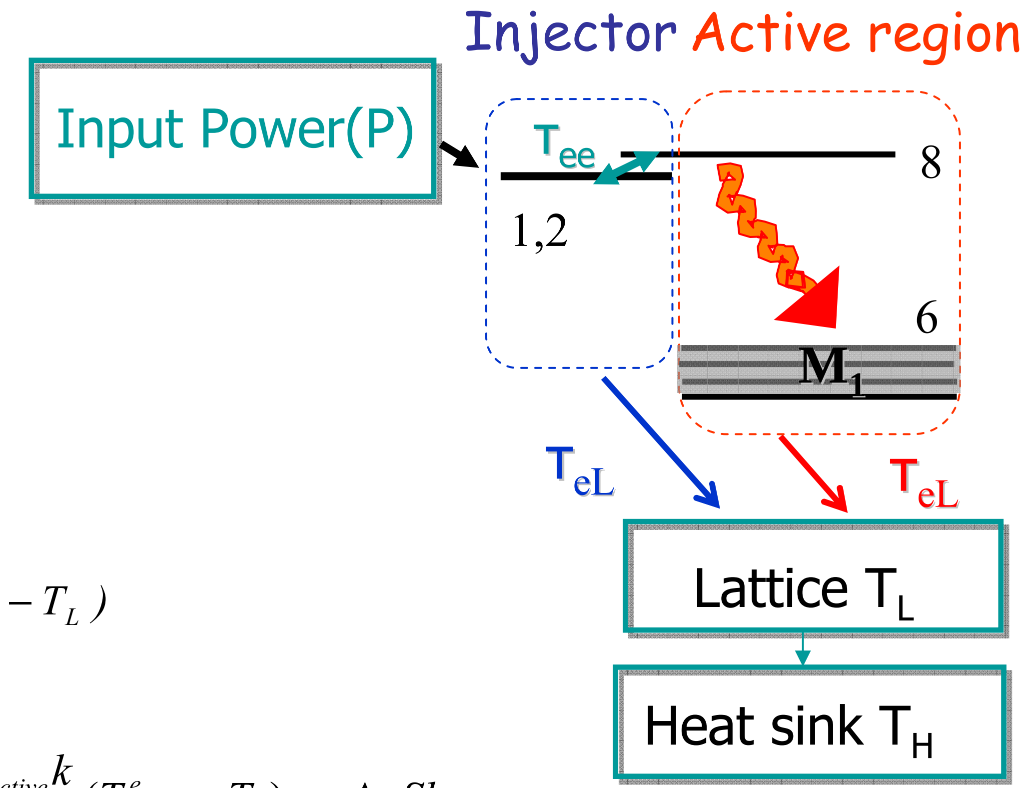
Sample B (140 µm × 1mm)



Energy balance in QCLs

$$\frac{dE_{tot}}{dt} = P - P_o - P_{th}$$

Electrical *Optical* *Thermal*



$$\frac{dE_{inj}}{dt} = \frac{J}{q}(kT^e_{active} - kT^e_{inj} + \Delta_1) - \frac{n_{inj}k}{\tau_{eL}}(T^e_{inj} - T_L)$$

$$\frac{dE_{active}}{dt} = \frac{J}{q}(kT^e_{inj} - kT^e_{active} + \Delta E_{86} + \Delta_{mb}) - \frac{n_{active}k}{\tau_{eL}}(T^e_{active} - T_L) - g\Delta nSh\nu$$

Present case $kT^e_{active} - kT^e_{inj} << \Delta_{mb} + \Delta E_{86}$

Hot electron cooling → probe of the laser efficiency

- Cooling of hot electrons in the active region is correlated with the internal quantum efficiency of a laser

$$\frac{d(T^e_{active} - T_L)}{dJ} \approx \frac{\tau_{eL}}{q n_{active} k}\left(\Delta E_{68} + \Delta_{mb}\right)$$

S= 0

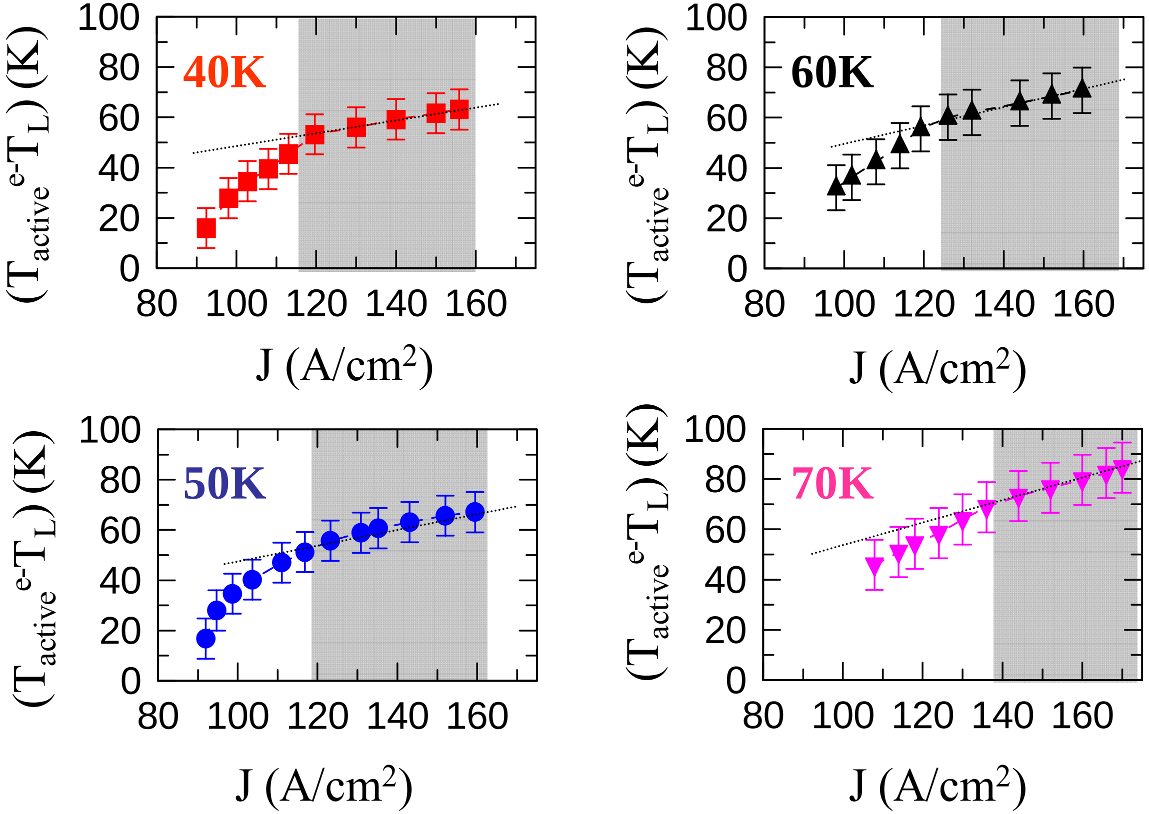
$$\frac{d(T^e_{active} - T_L)}{dJ} = \frac{\tau_{eL}}{q n_{active} k}\left(h\nu + \Delta_{mb} - h\nu\eta_{int}\right)$$

S≠ 0

$$\eta_{int} = \frac{\tau_8\left(1 - \frac{\tau_6}{\tau_{86}}\right)}{\tau_8\left(1 - \frac{\tau_6}{\tau_{86}}\right) + \tau_6} = \alpha_{tot} \cdot \frac{dS}{dJ} \cdot q$$

Internal quantum efficiency

Temperature dependence of T^{e}_{active}



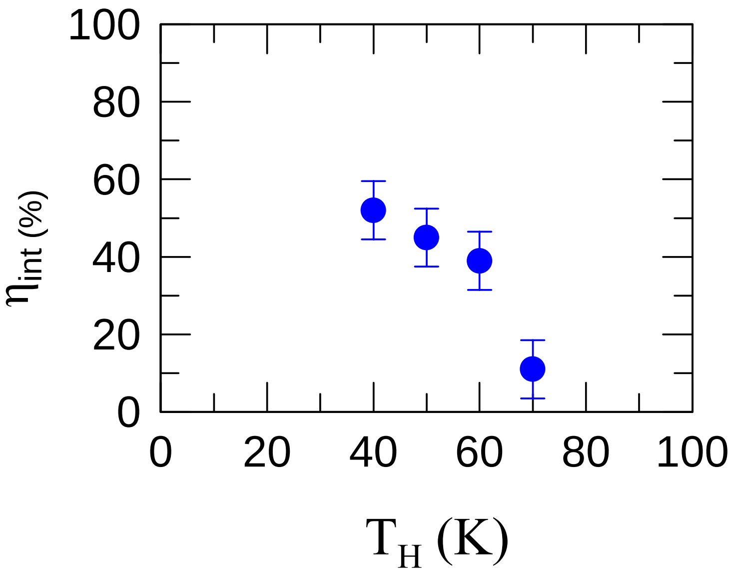
At increasing T_H, the slope $d(T_{active}^{e}-T_L)/dJ$ above lasing threshold increases → laser cooling less effective

Internal quantum efficiency η_{int}

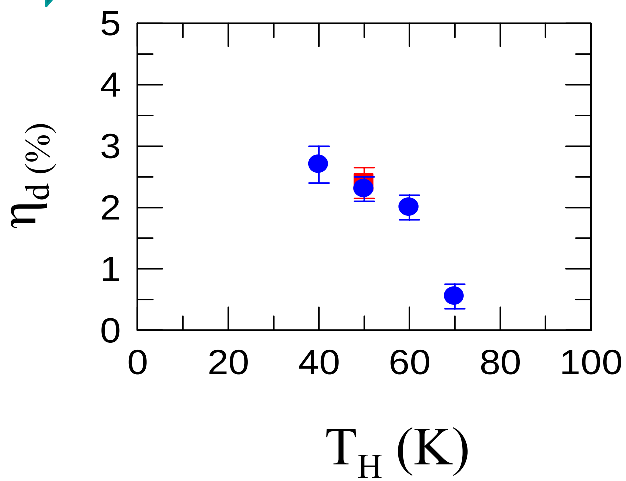
$$\eta_{int} = \left(1 - \frac{d(T_e^{active} - T_L)}{dJ}\frac{n_{active}kq}{\tau_{eL}(h\upsilon + \Delta_{mb})}\right)\frac{(h\upsilon + \Delta_{mb})}{h\upsilon}$$

$$\eta_d = \eta_{int}\frac{\alpha_m}{\alpha_{tot}}$$

Internal quantum efficiency



Differential external quantum efficiency per stage



Comparison with alternative experimental approaches

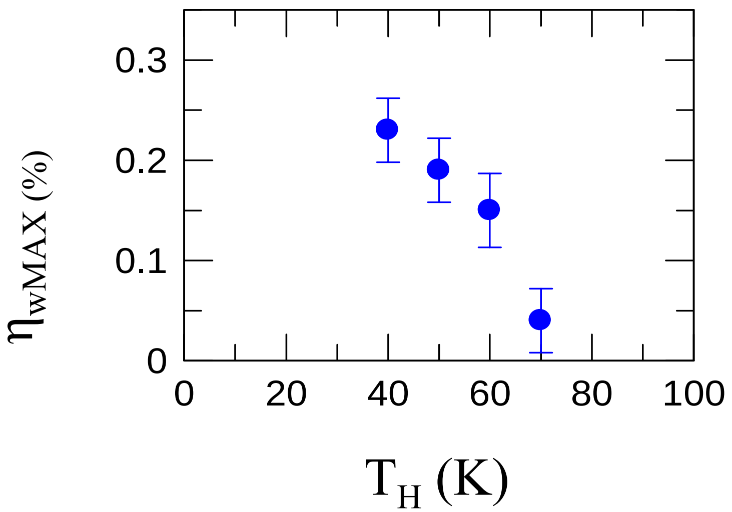
- The measured efficiency values are a factor ≈ 4.5 larger than those obtained by conventional optical measurements
- Optical testing → inherently limited by:
  - the small collection efficiencies of the optical set-ups
  - the high optical beam divergence of metal-metal waveguides
- Alternative approaches → relative change in the differential resistance above and below threshold

$$\left(\eta_{int} = 1 - \frac{\Delta R}{R}\right)$$

- Due to residual resistances in the device understimation of ≈ 40% in the internal quantum efficiency have been obtained

Wall-plug efficiency

$$\eta_w = \eta_{\text{int}} \frac{\alpha_m}{\alpha_{tot}} \frac{Nh\nu}{e} \frac{1}{V}\left(1 - \frac{J_{th}}{J}\right)$$



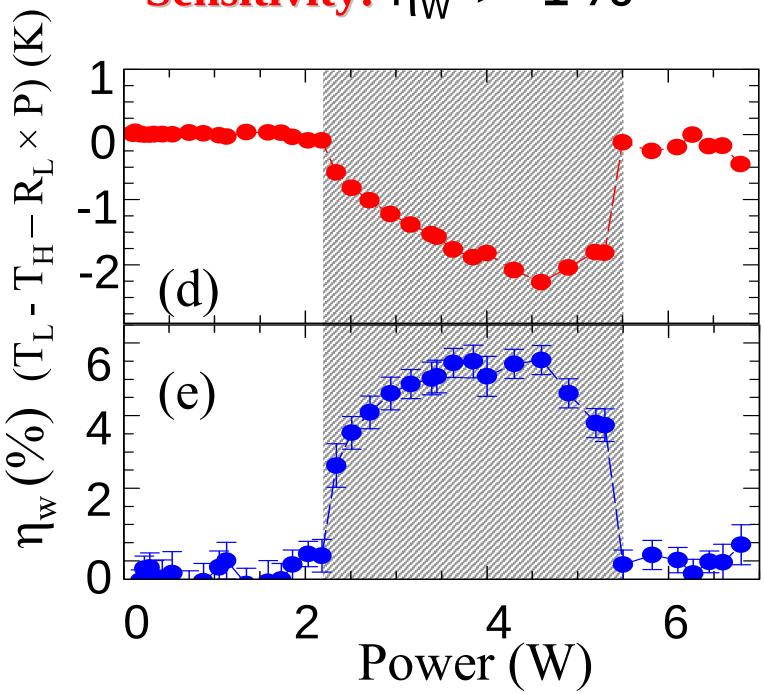
Hot electron probe → **Higher sensitivity**, particularly useful in the characterization of terahertz sources with highly diverging beams like **double-metal QCLs**.

Our thermal self-calibrated approach in *surface plasmon THz QCLs*

- Deviations from the thermal resistance trend in the lasing range → $P_{thermal}$ → η_W

$$\eta_w = 1 - \Delta T/(P_{in} \times R_L)$$

Sensitivity: $\eta_W > 1\%$



M.S.Vitiello, et al.APL 90, 191115 (2007)

Alternative gain media

- The processes observed in the terahertz QCLs are quite general and can be conveniently extended also to other gain media

- Double-heterostructure interband lasers → carrier heating by Auger recombination plays a very fundamental role

  - The hot carrier cooling rate may be much slower than the energy loss rate by phonon emission

  - The excited level temperature increase well above the one of the lattice or the carrier reservoir

  - Less abrupt change of the heating rate at threshold is expected → a significant amount of power is extracted from the laser via spontaneous emission processes even below threshold.

Summary

- Experimental evidence of a new physical phenomenon characteristic of semiconductor lasers: the cooling of the electrons above the laser threshold for stimulated emission
- Correlation between the hot electron cooling and the internal quantum efficiency of a laser
- Self-calibrated approach to extract the internal quantum efficiency and the wall-plug efficiency in a QCL
- Implications →
  - Inclusion of the electronic temperature in the general theory of semiconductor lasers
  - Hot-electron effects must be fully understood in THz QCL to explore the device physical limits in terms of maximum temperature, wavelength and quantum efficiencies.