The quantum cascade laser: a semiconductor laser operating in the 3 to 300µm wavelength range

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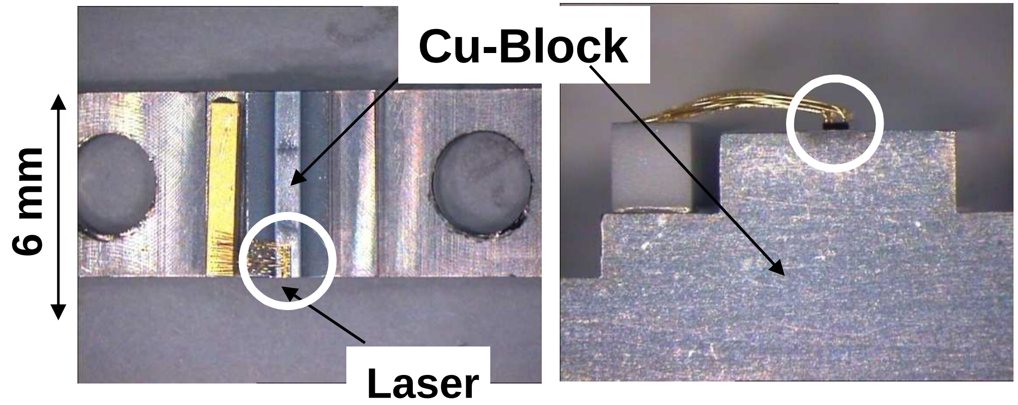
QC laser's birthday: 14 / 01 / 1994

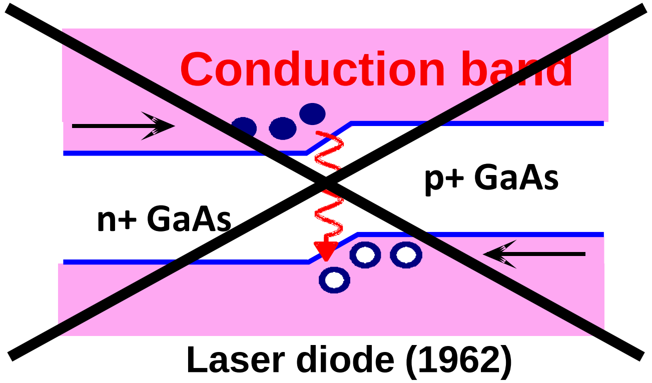
Photo taken by Federico Capasso (the *Boss*) after a night of work.

The quantum cascade lasers

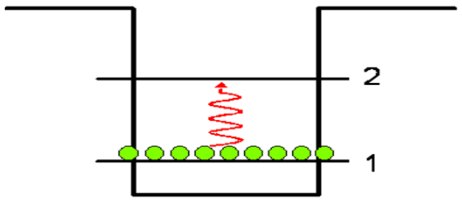
1. Is an electrically injected semiconductor laser



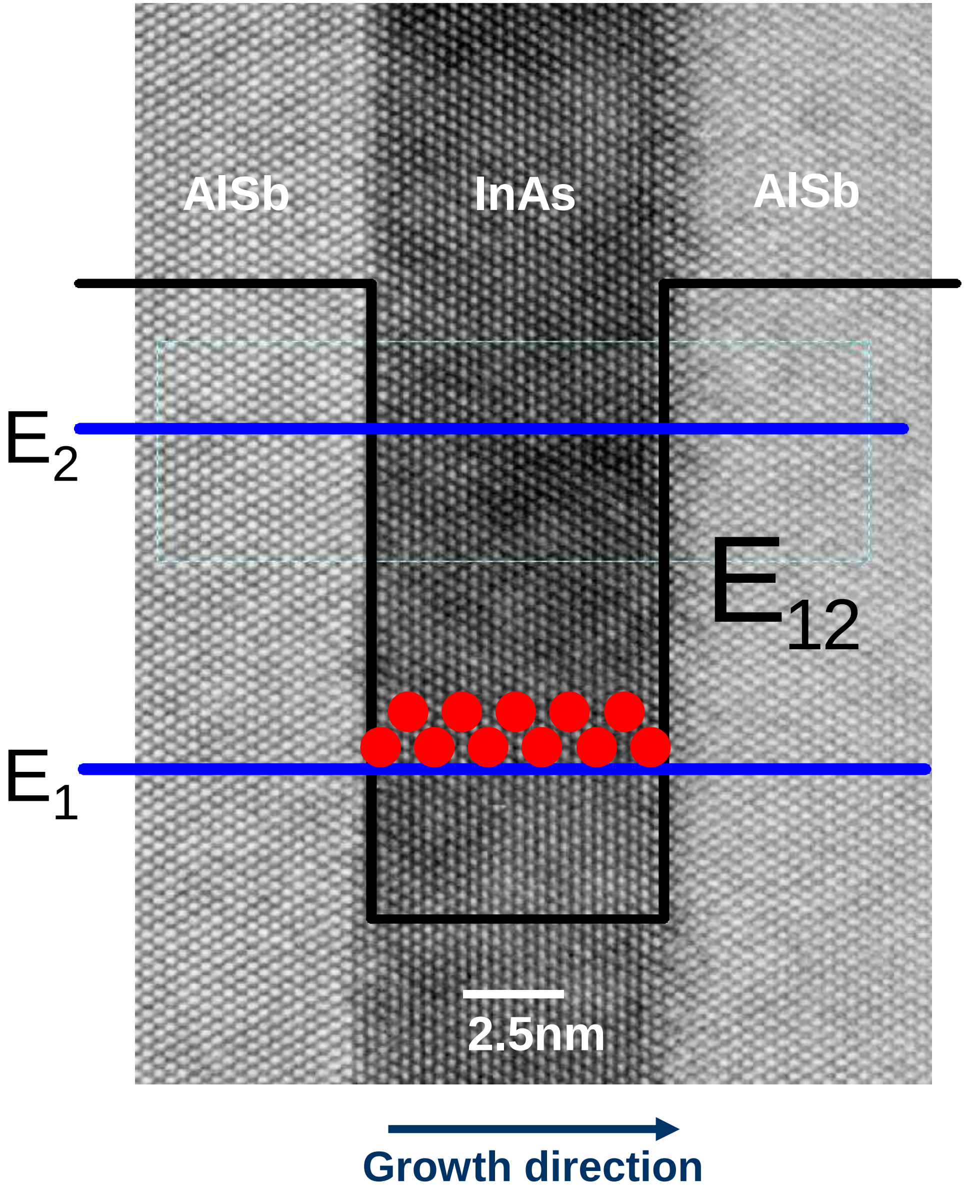
2. Radiative transitions occur in the conduction band



3. Low dimensional structures with electrons only (unipolar)



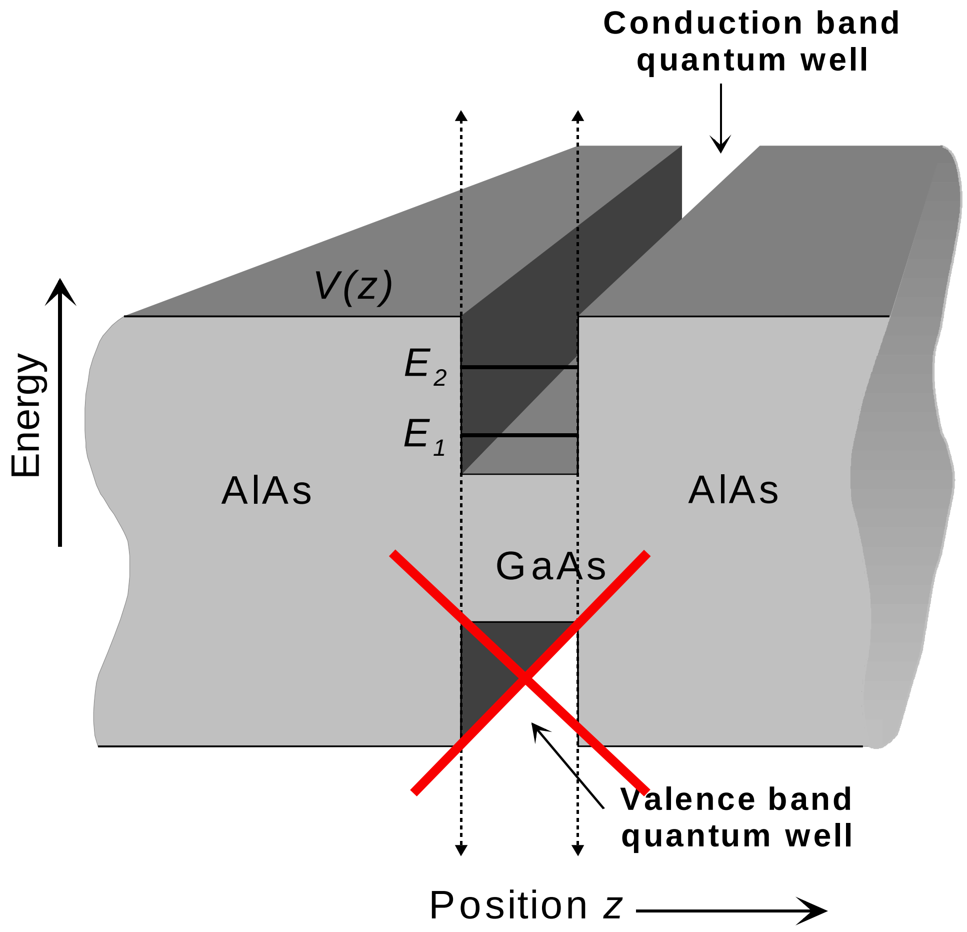
The quantum well: the building block

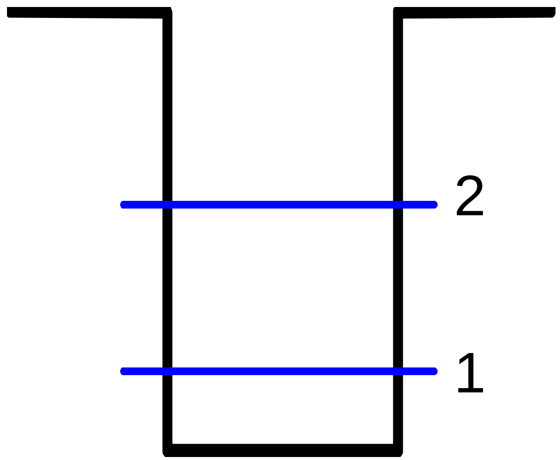


The quantum well is the elementary constituent of our system

Light-matter interaction with photon energies lower than the band gap

Energy vs. position in a quantum well structure





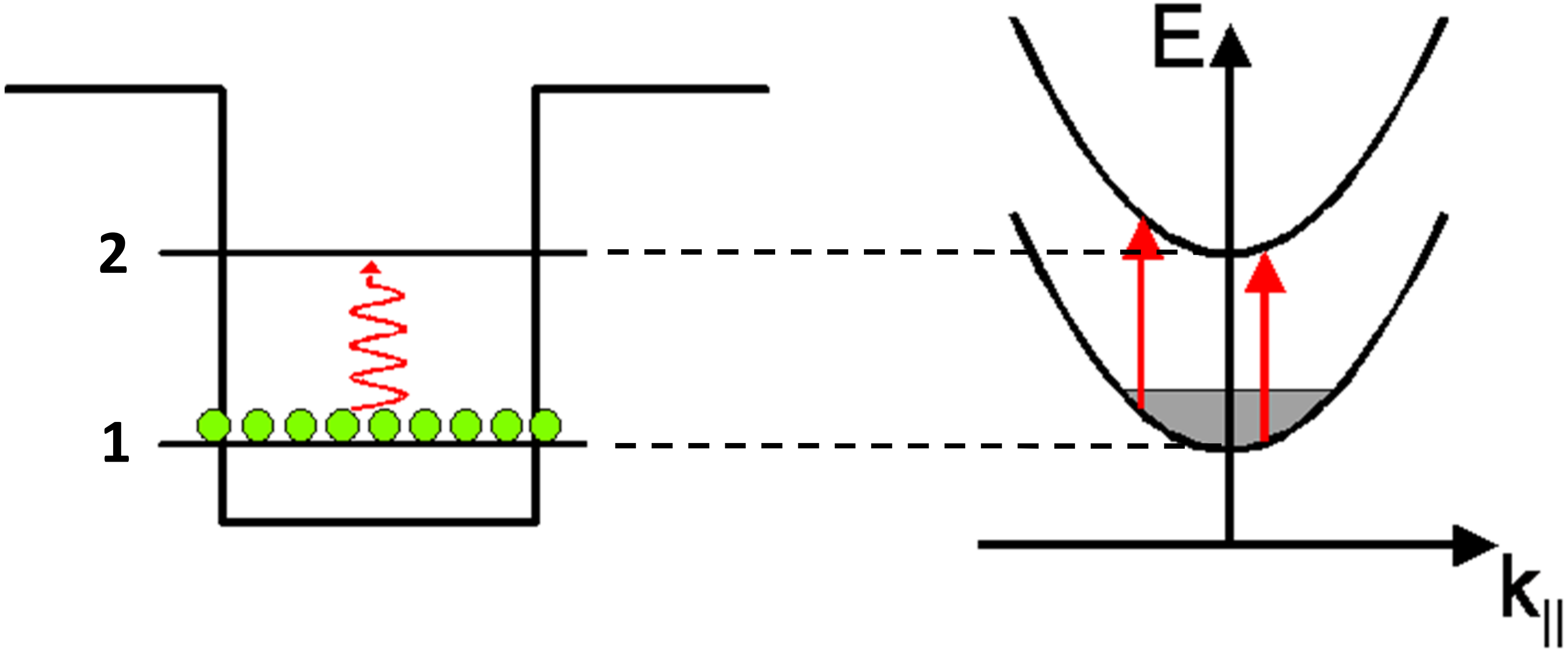
The confinement potential is only in the direction of growth (*z*)

Electrons are free particles in the plane

Intersubband absorption

The absorption of a photon is related only to the energy difference between the subbands et does not depends on $k_{//}$

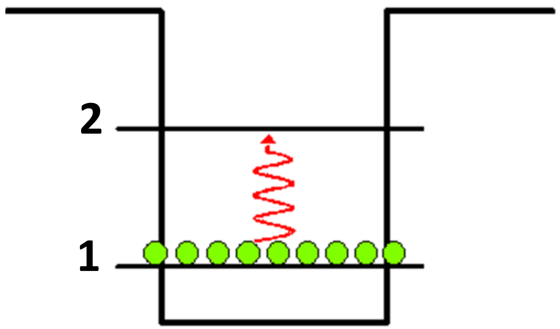
$$E_{n,k} - E_{m,k} = E_{nm}$$

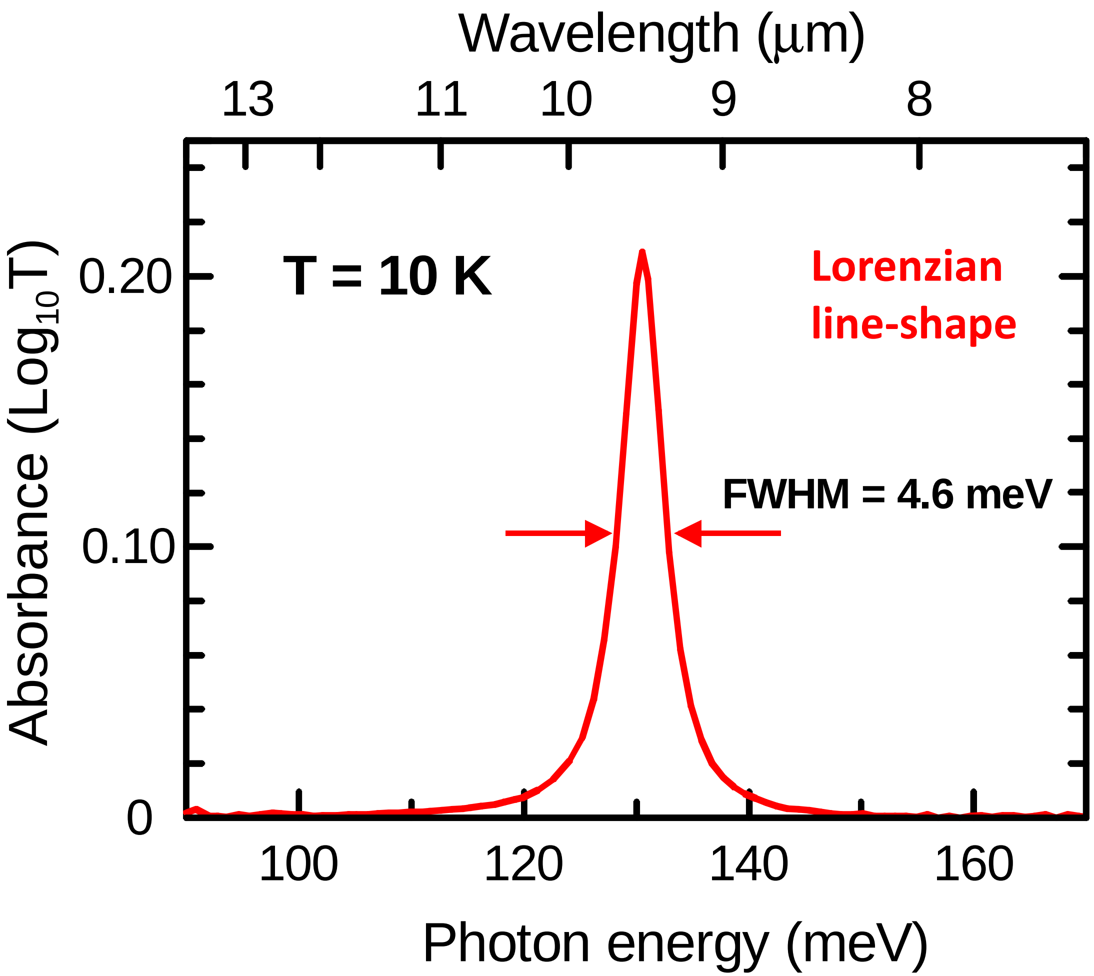


- **Absorption peaks like in 3D confined potentials : atoms**
- **Zero dimensional joint density of states**

Absorption measurements

Modulation doping allows to observe narrow lines $\frac{\Delta E}{E_{12}} \cong 5\%$





Far Infrared Optics in Si-Inversion layers

VOLUME 32, NUMBER 22 PHYSICAL REVIEW LETTERS 3 JUNE 1974

Resonance Spectroscopy of Electronic Levels in a Surface Accumulation Layer

A. Kamgar, P. Kneschaurek, G. Dorda,* and J. F. Koch
Physik-Department, Technische Universität München, 8046 Garching, West Germany
(Received 25 March 1974)

Resonance transitions are observed between electronic levels in an accumulation layer on n-type (100) Si. Signals are studied at the 220-, 171-, and 118-μm lines of a water-vapor (H_2O, D_2O) molecular laser. Strong transitions from the lowest two-dimensional sub-band to the next higher band are observed. For 118-μm radiation the resonance occurs at about 0.6×10^{12} electrons/cm^2.

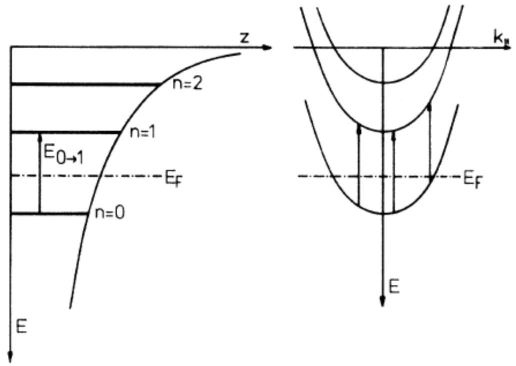
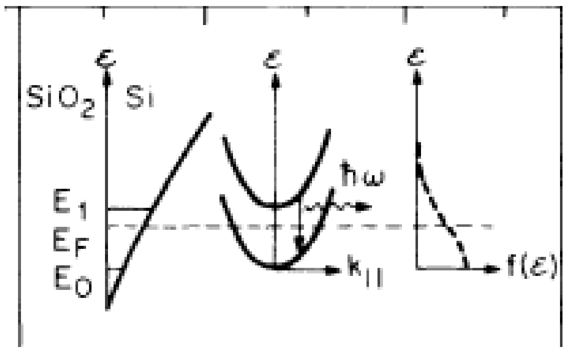


FIG. 2. Surface potential well and energy levels for an accumulation layer on n-type (100) Si. For a surface charge density of 10^{12} electrons/cm^2 the energy-level separations are on the order of 10 meV and only the first sub-band is occupied. Possible transitions between the parabolic two-dimensional sub-bands are indicated.



VOLUME 37, NUMBER 21 PHYSICAL REVIEW LETTERS 22 NOVEMBER 1976

Voltage-Tunable Far-Infrared Emission from Si Inversion Layers

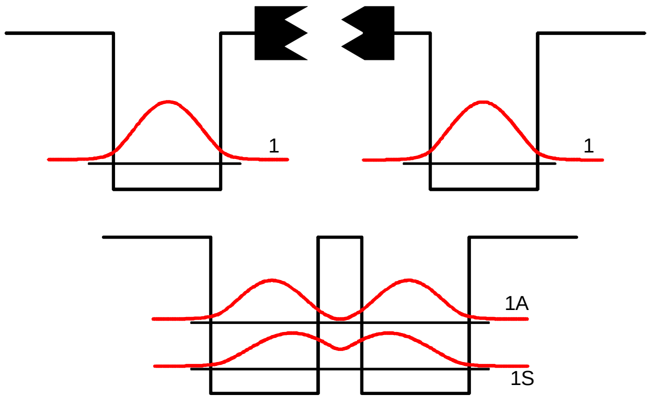
E. Gornik and D. C. Tsui
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 7 September 1976)

We have observed voltage-tunable far-infrared emission from inversion layers of n-channel metal-oxide-simiconductor field-effect transistors fabricated on p-type (100) Si. The radiation is emitted by the electronic transition from the two-dimensional excited-state E_1 sub-band of the inversion layer to its ground-state E_0 sub-band. Population of the excited-state sub-band is realized by heating up the electron distribution with an electric field applied along the channel.

Coupled-quantum-wells quasi molecules

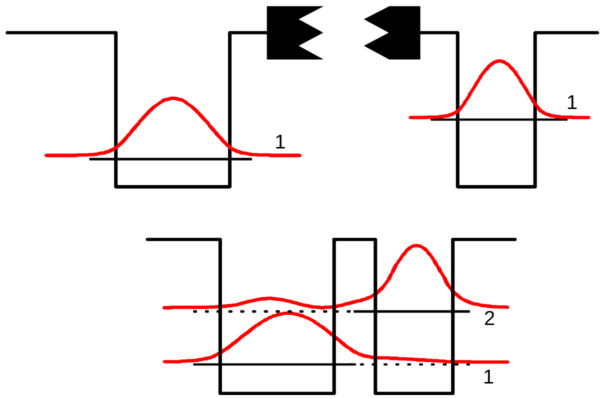
Quantum engineering of intersubband transitions is enabled
by coupling of quantum wells through thin tunneling barriers:

Symmetric coupled-quantum-wells



Formation of a symmetric and antisymmetric doublet

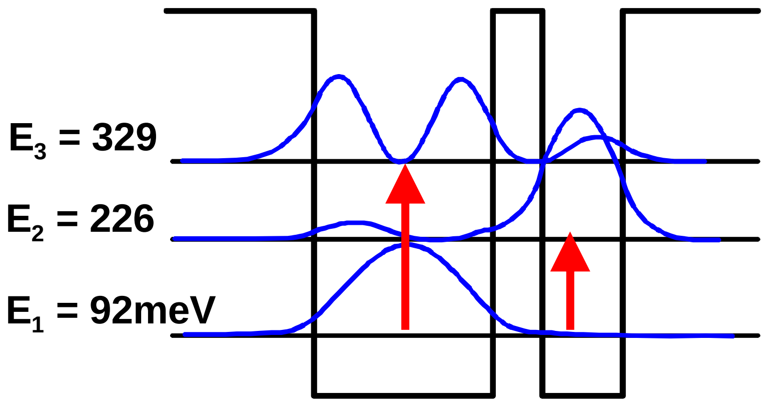
Asymmetric coupled-quantum-wells



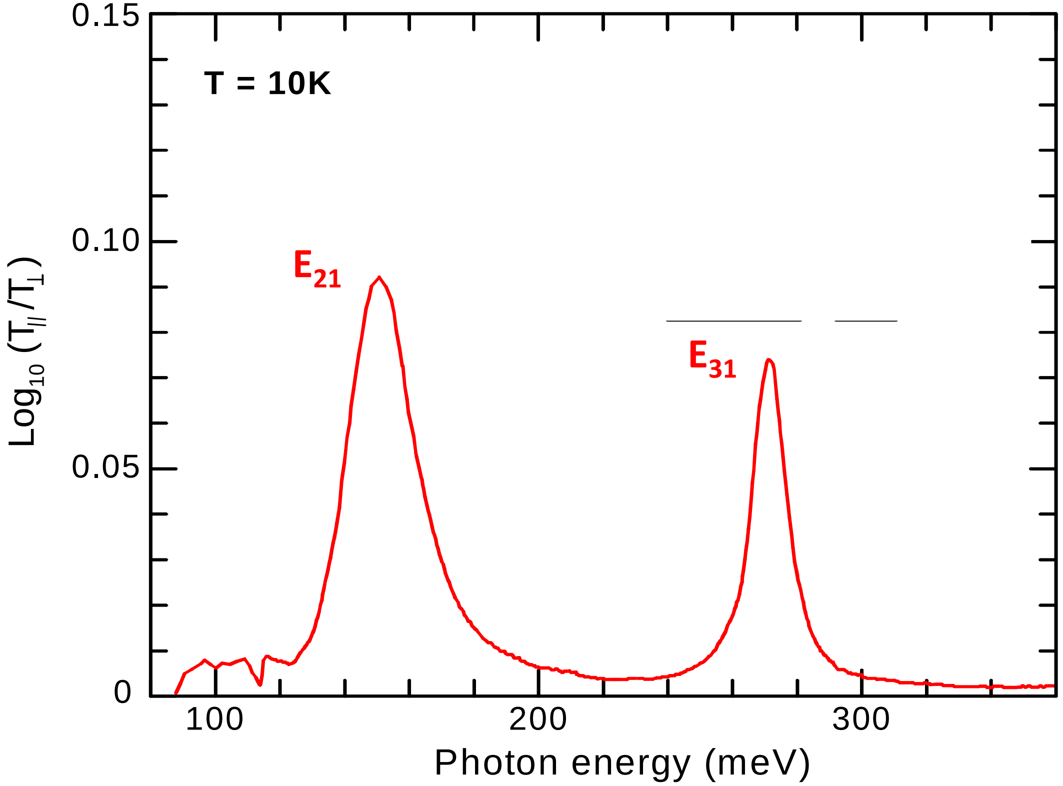
Hybridisation of orbitals with different quantum numbers

$$H_0 = H_{crystal} + V(z) + V_{field} + V_H = \frac{p^2}{2m^*} + V(z) + eFz + V_H$$

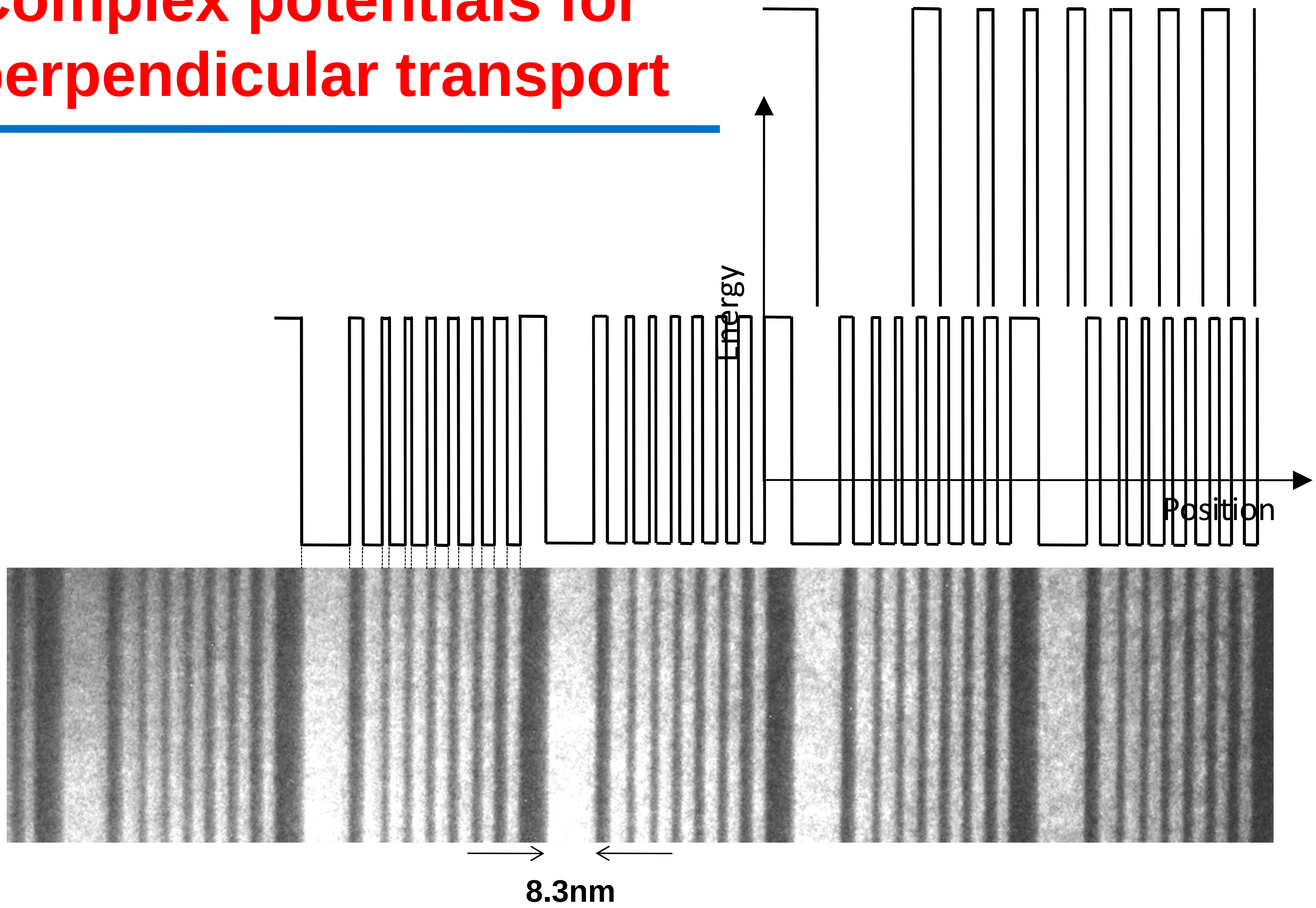
Two-coupled-quantum wells



The wavefunctions are coherent across a thin tunnel barrier



Complex potentials for perpendicular transport

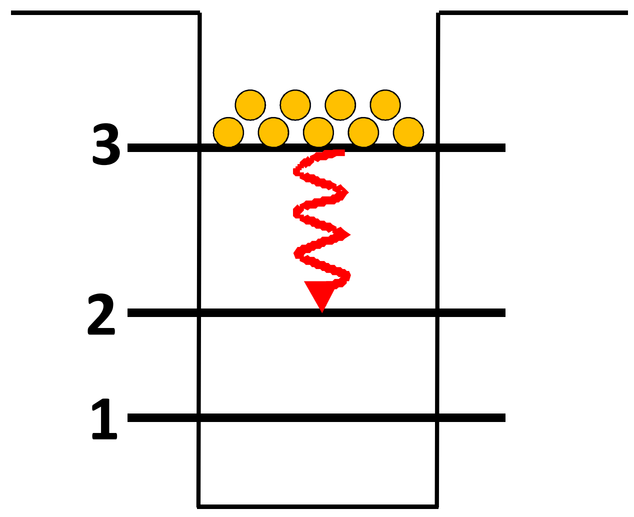


TEM Courtesy of I. Sagnes, LPN

Quantum Cascade lasers

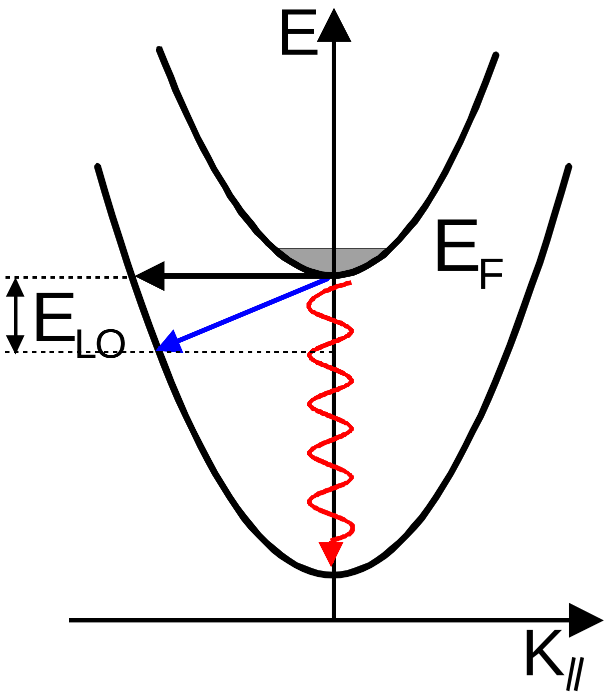
Population inversion between subbands

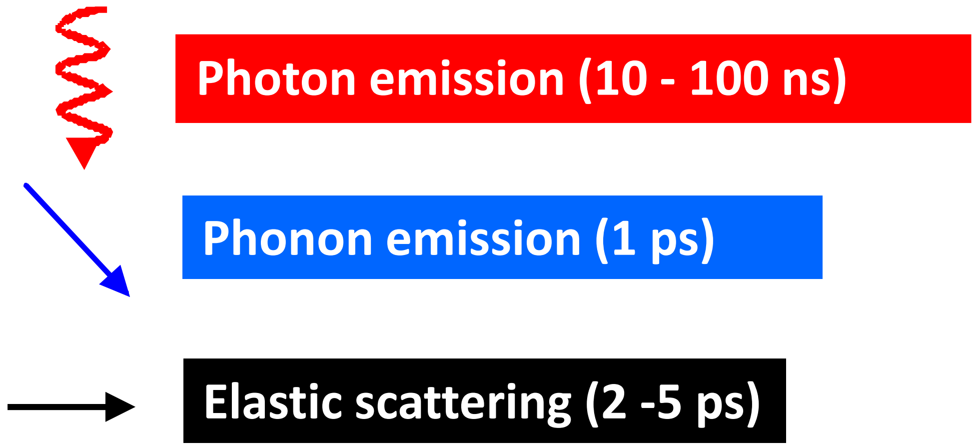
0-order approximation



- Population inversion between two excited subbands
- Electrically injection

Intersubband lifetime



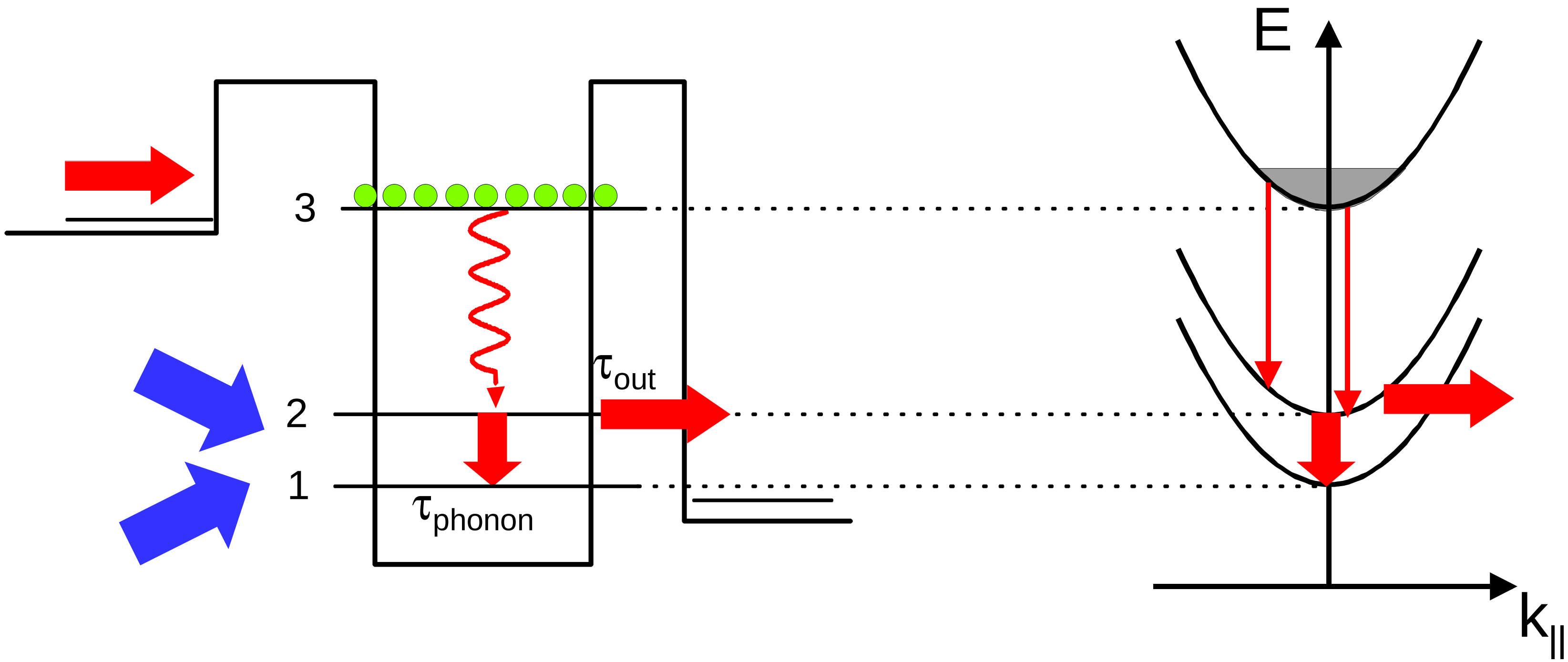


Electrons leave excited subbands by spontaneous emission of optical phonons (bleu arrow)

This time can be estimated using bulk phonons

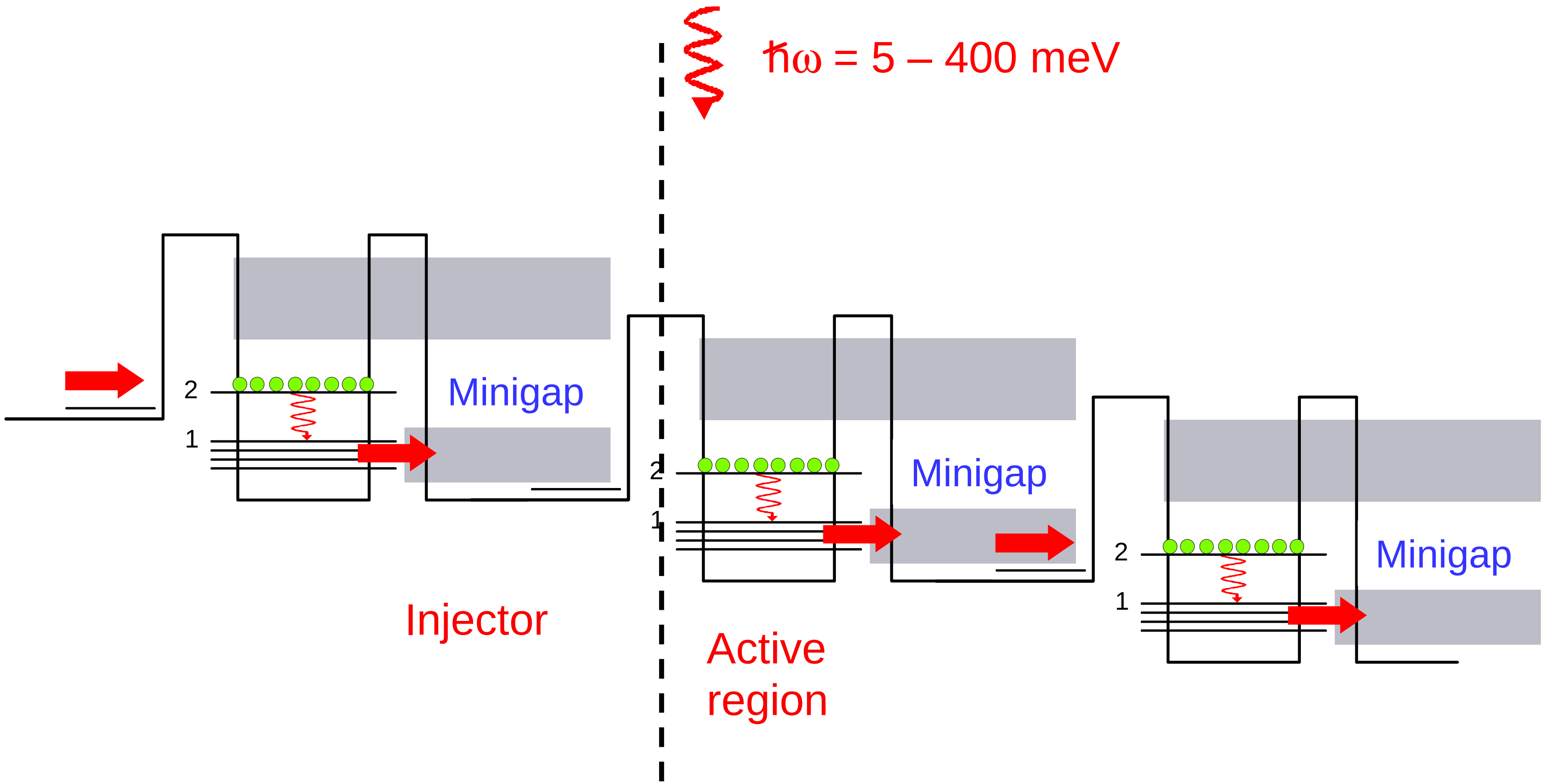
Radiative efficiency = 10^{-4} - 10^{-5}

Population inversion between subbands



- Injection and extraction of electrons from quantum wells by tunnelling
- Population inversion condition $\tau_{32} > \tau_2$

QC laser design



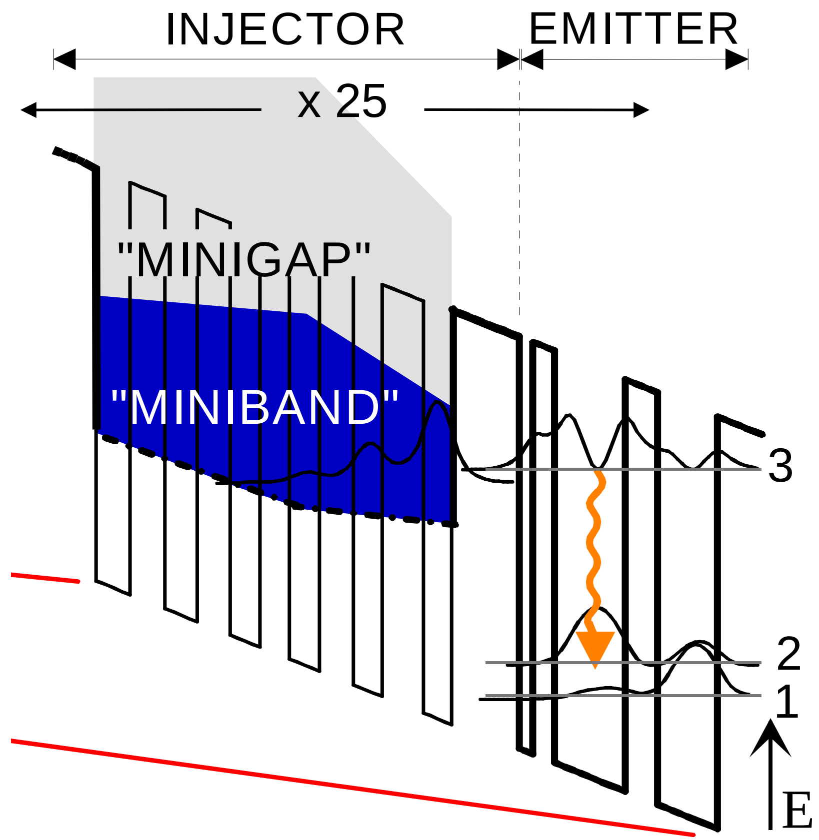
Cascade Action:

1) N_p photons per electron traversing the structure (N_p ~100 @THz)

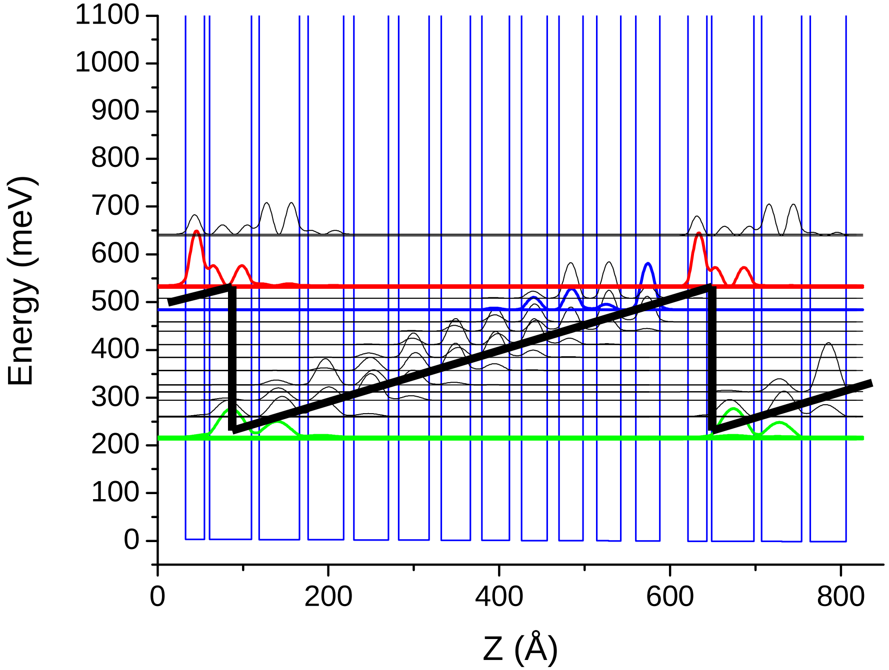
2) The total population inversion is distributed over all the period

Quantum cascade design and material

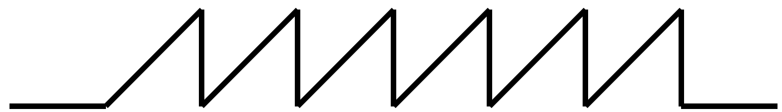
Band diagram



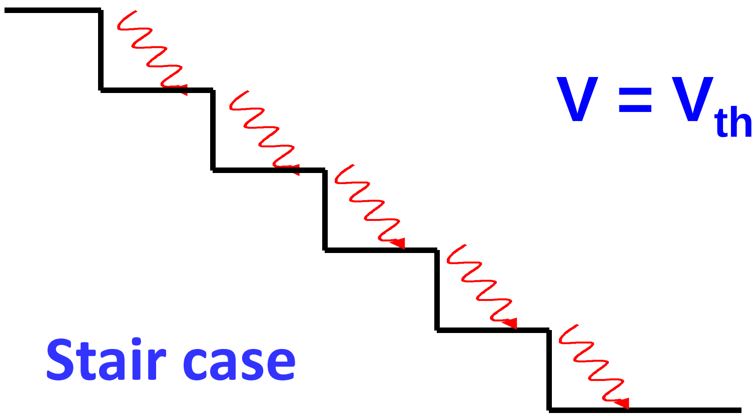
Applied bias on a QC laser (λ = 4.3μm)



V = 0

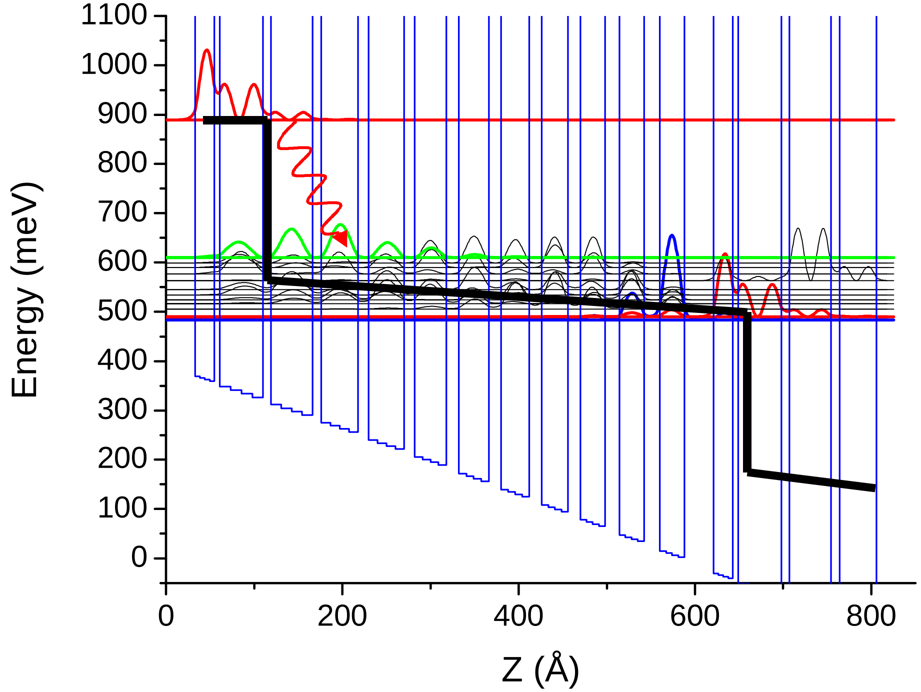


Saw tooth



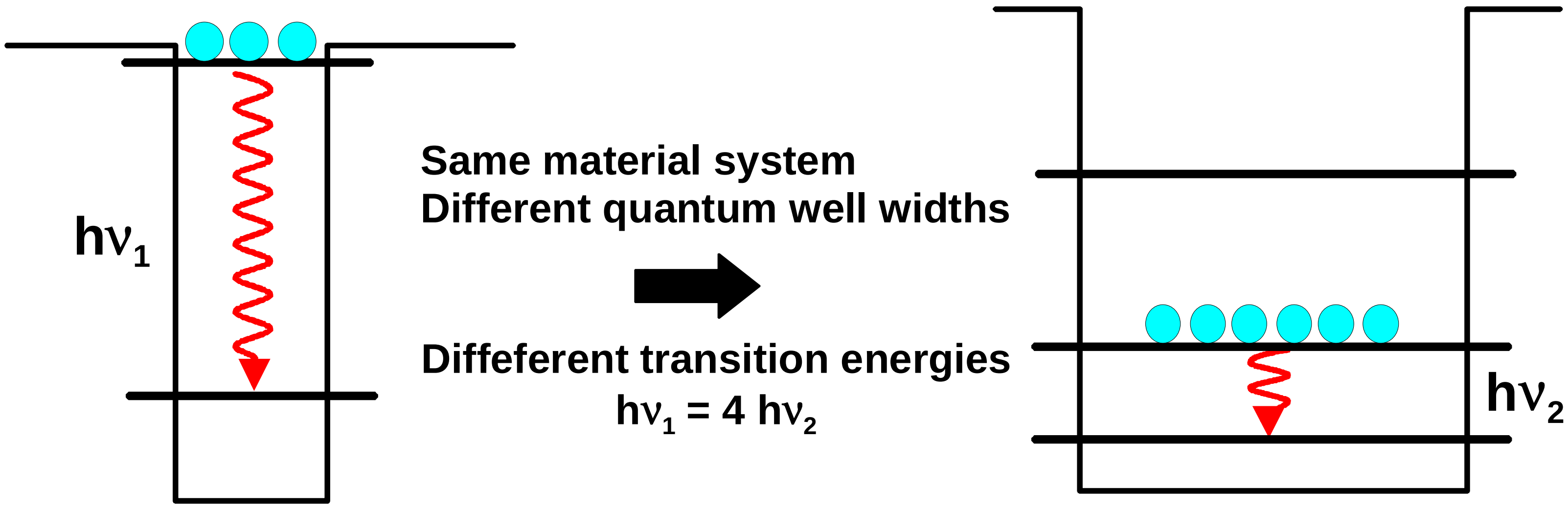
$V = V_{th}$

Stair case



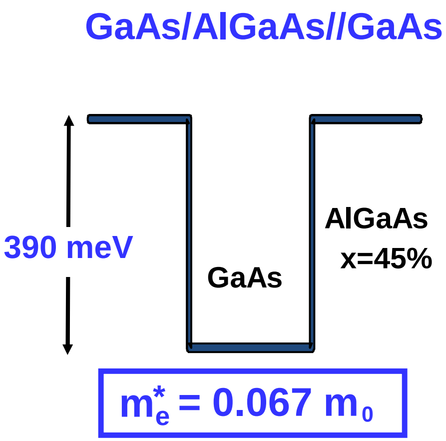
Wavelength agility

Intersubband transition energies



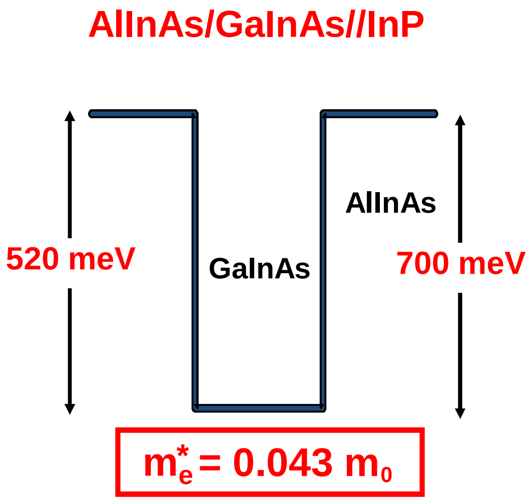
Energy separation between the levels depend on the quantum well width and not on the materials constituent the heterostructure

Material systems for QC laser



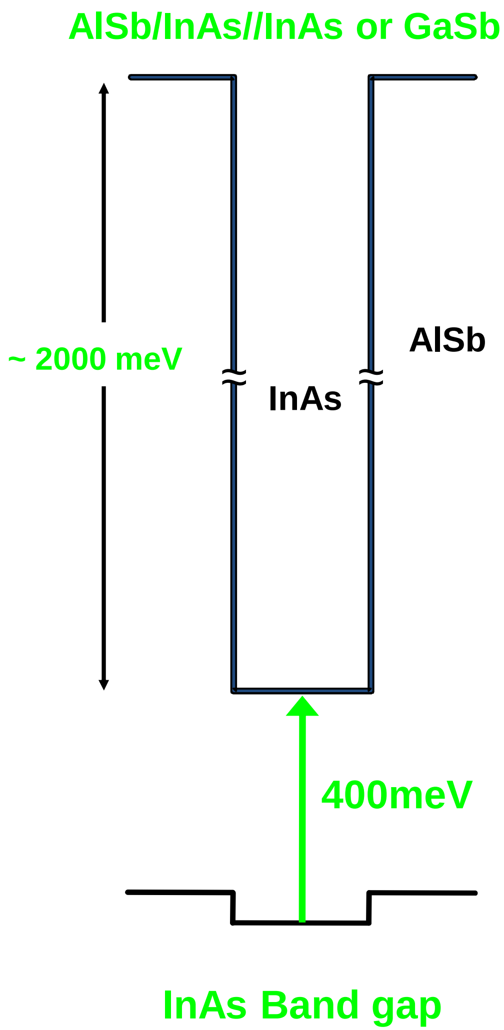
GaAs/AlAs
~ 1000meV

Indirect discontinuity limits to 400meV



AlInAs/GaInAs/InP
strain compensated
~ 600/700 meV

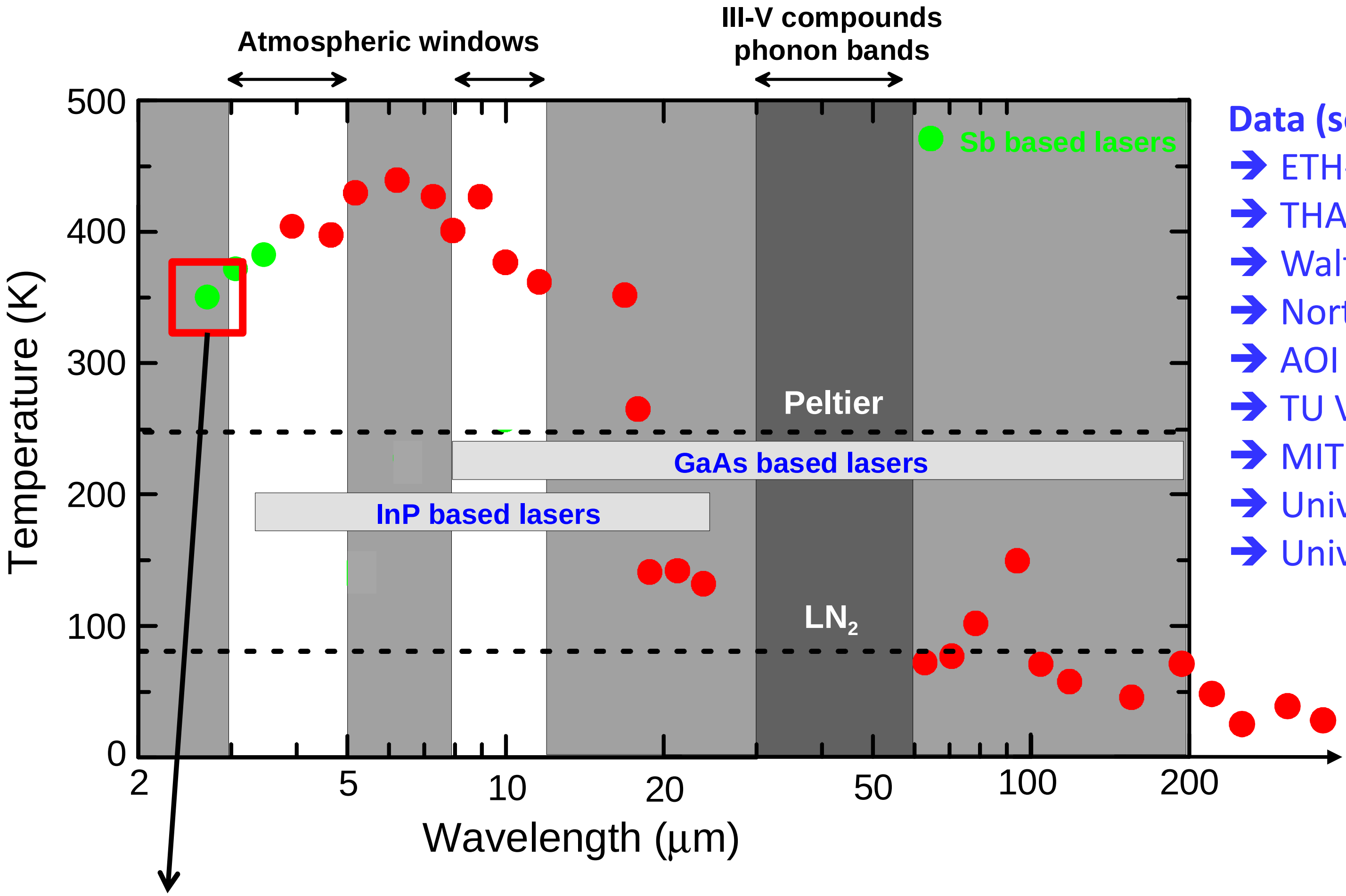
Even in strain compensated materials no evidence of lateral valleys



GaN?

T_{max} of QC lasers vs. wavelength

Pulsed operation



Uni. Montp. 2.6µm!

Data (some are unpublished):

- ➔ ETH-Z
- ➔ THALES
- ➔ Walter Schottky (Munich)
- ➔ Northwestern University
- ➔ AOI (Houston)
- ➔ TU Vienna
- ➔ MIT
- ➔ University of Sheffield
- ➔ University of Montpellier

Range of operation:

2.7 - 400µm or 100 – 0.8THz

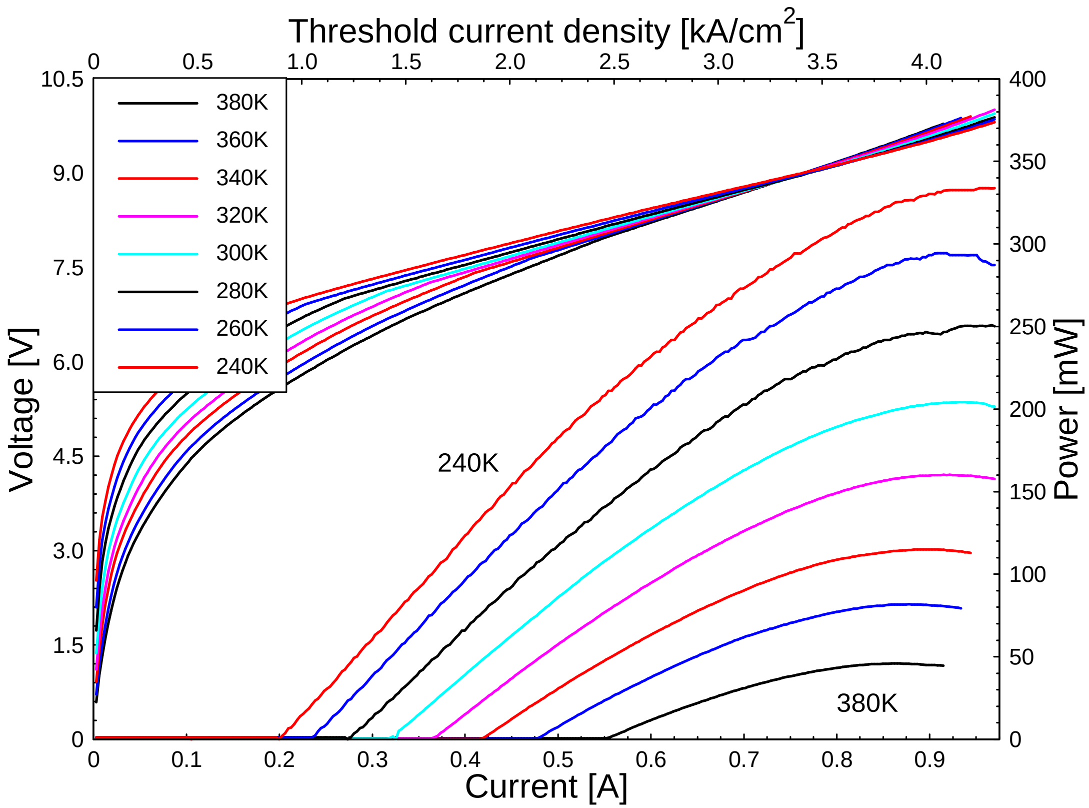
Quantum Cascade laser performances

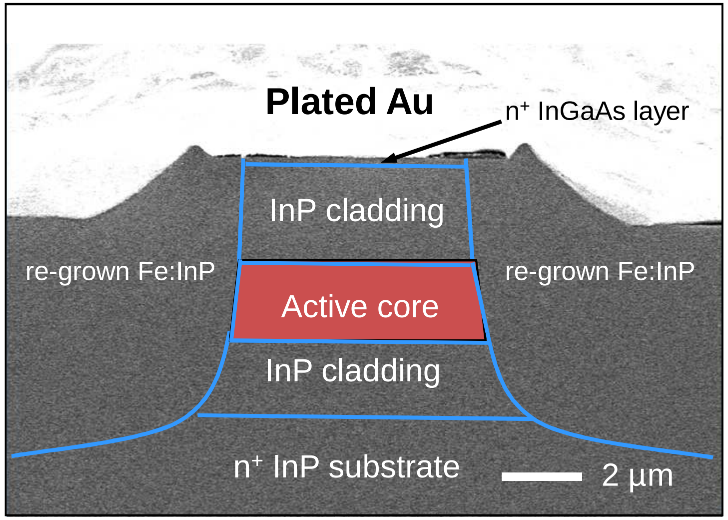
QC laser performances

- **Threshold Current**
  - Lowest possible
- **Emitted Optical power**
  - Highest possible within a well defined spatial mode
- **Wall plug efficiency** = $\dfrac{\textbf{Optical power}}{\textbf{Electrical power}}$
  - Highest possible to limit thermal stresses
- **Spectral and spatial control**
  - Monomodo operation : single frequency and single lobe
- **Reliability**
  - Monomodo operation : single frequency and single lobe

Burried heterostructures

for optimum power dissipation

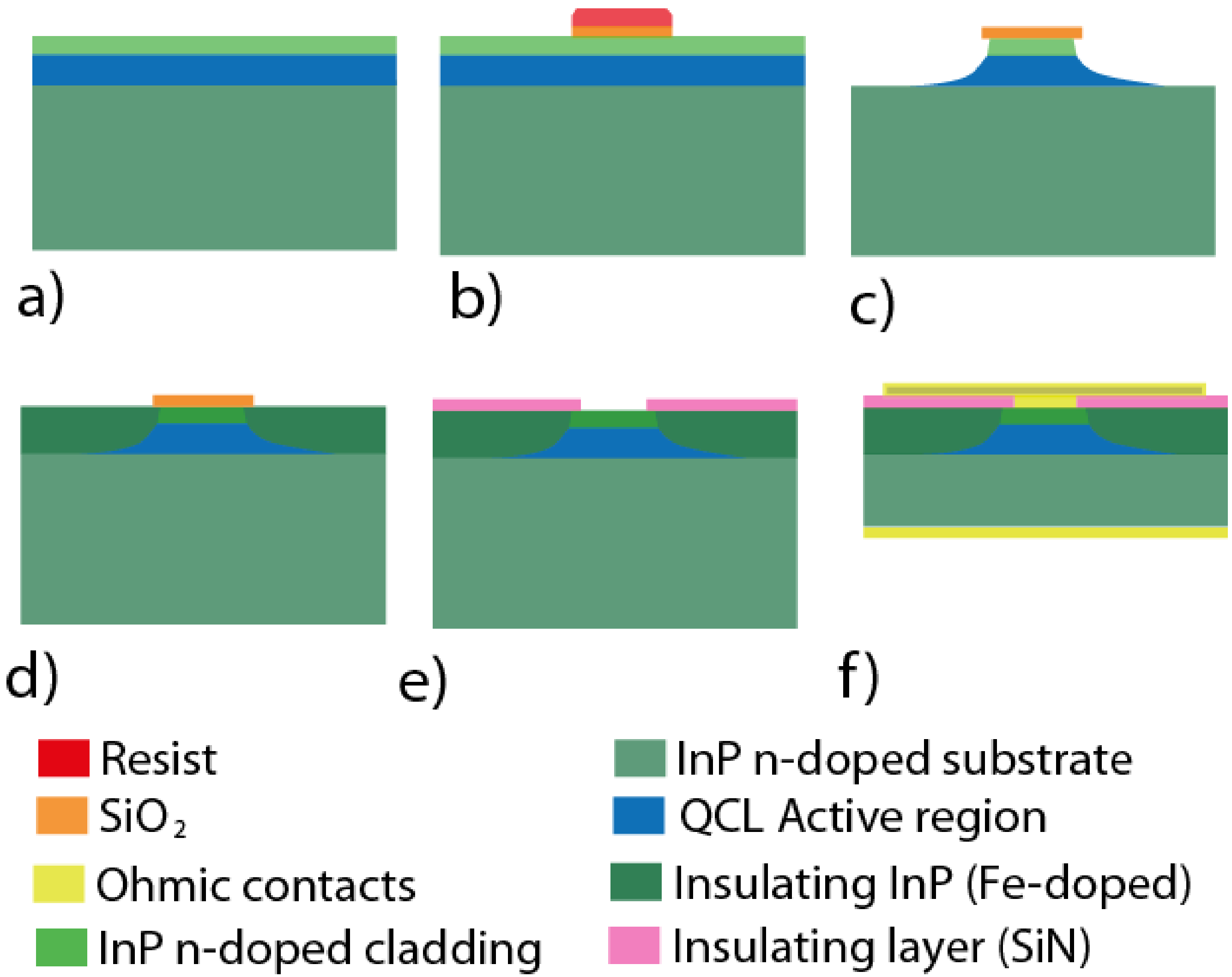




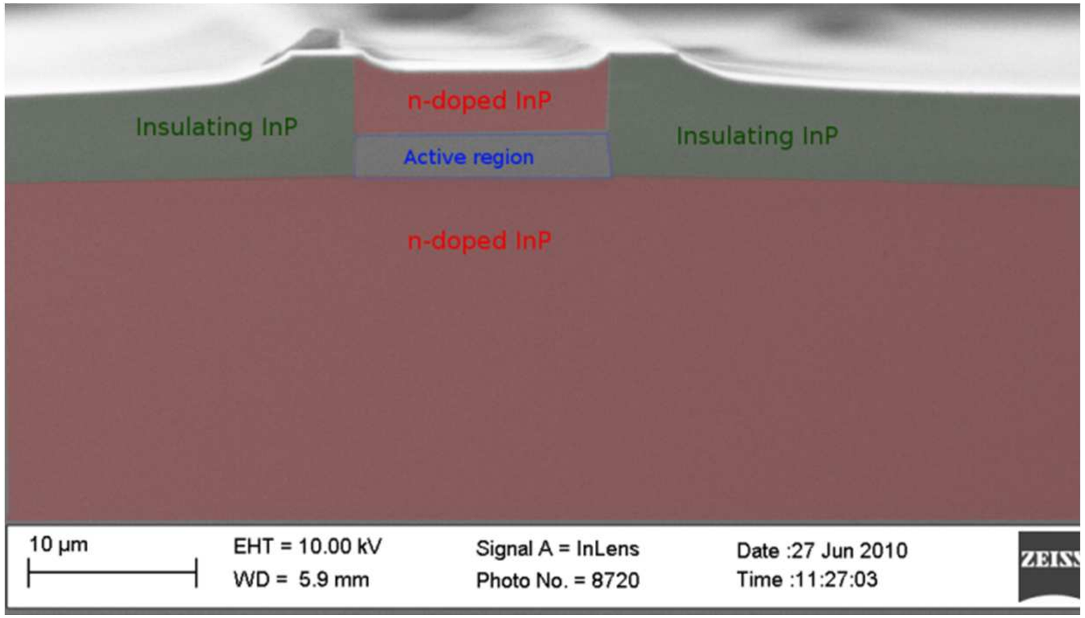
Burried heterostructures for optiumum power dissipation

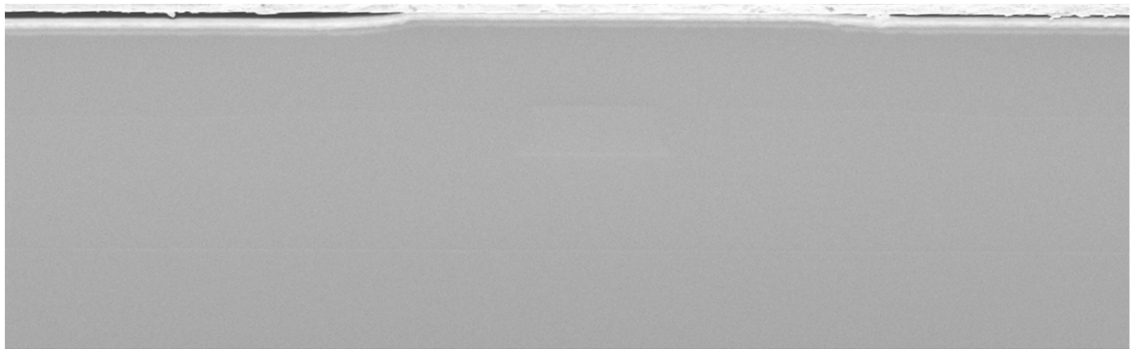
L. Dhiel et al. APL (2006)

Burried heterostructures

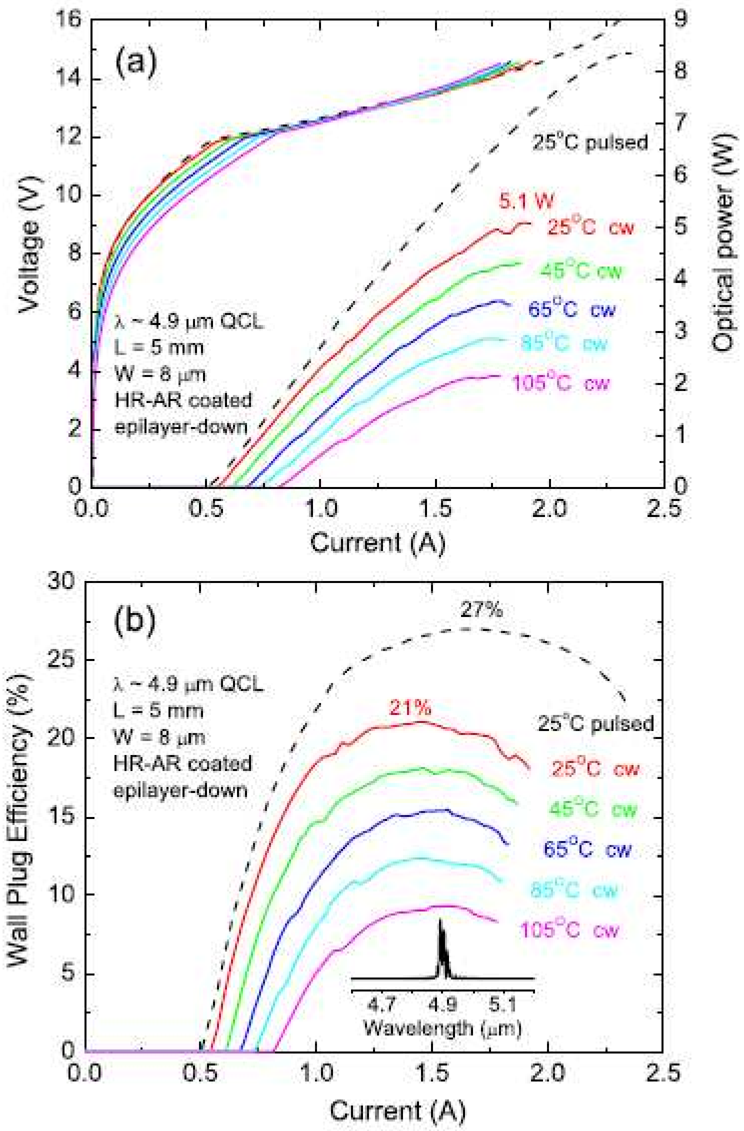


Burried heterostructures SEM Picture





CW operation of QC lasers (State-of-the-art)



27% wall plug efficiency!

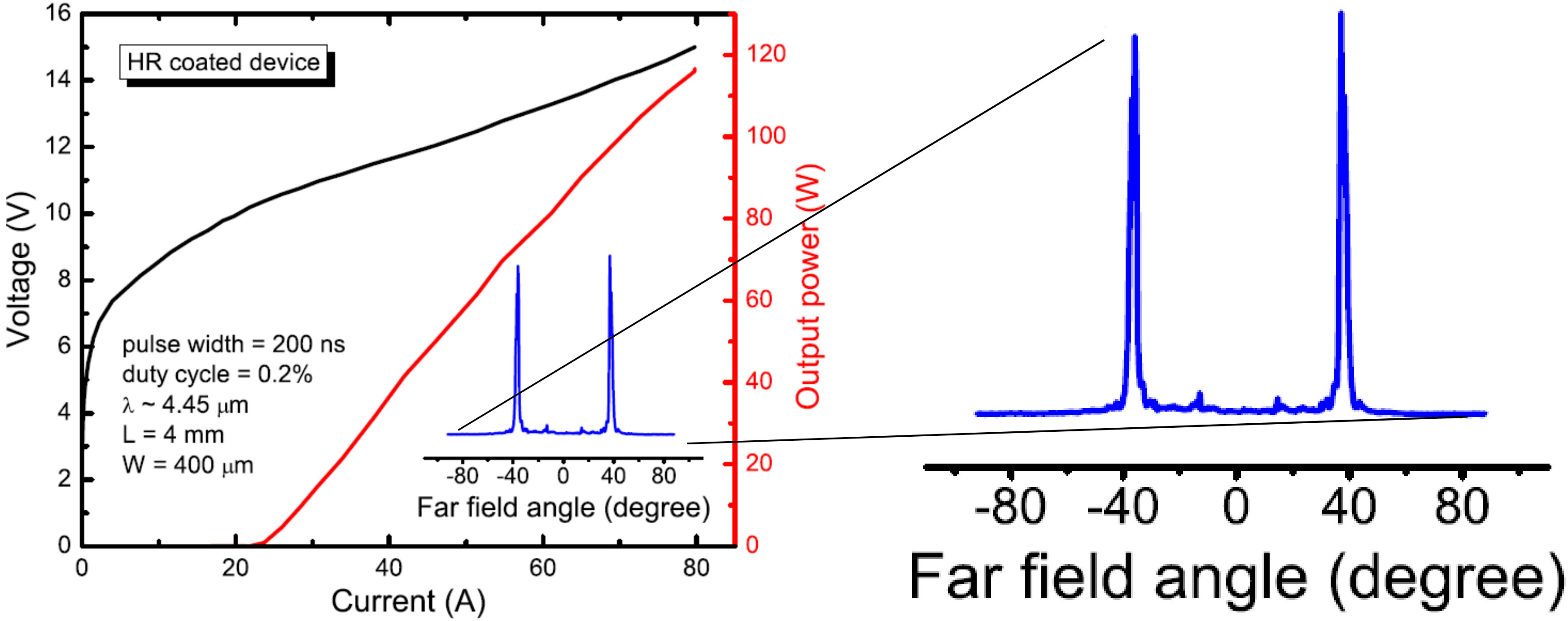
Y. Bai, et al., APL **98,** 181102 (2011)

NORTHWESTERN UNIVERSITY

CQD

Very High power broad area QCLs

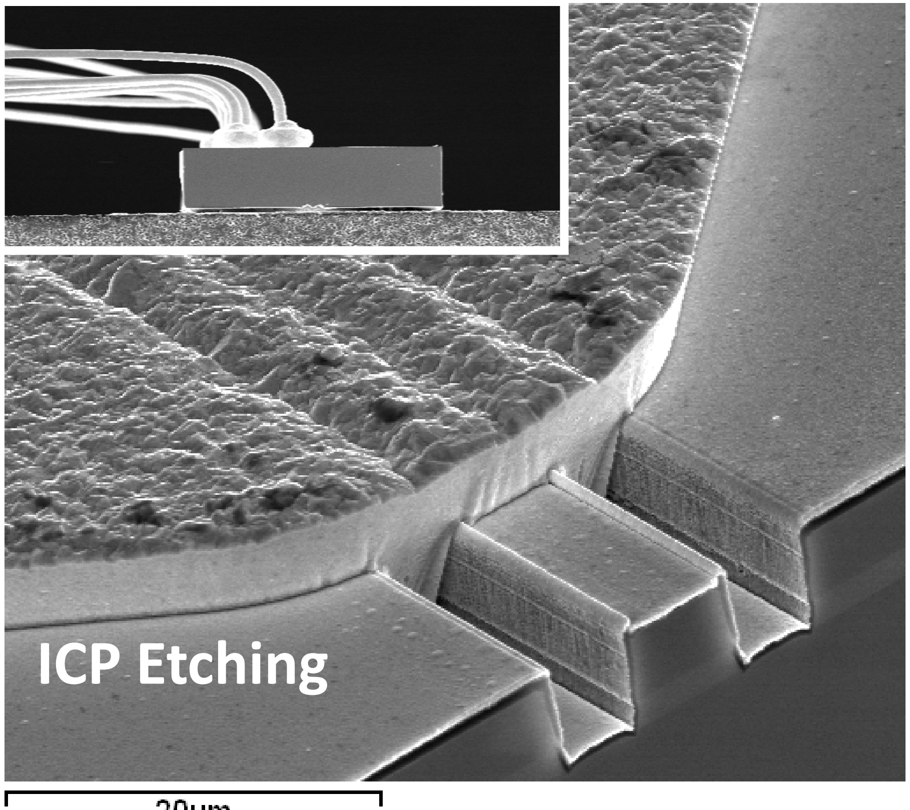
Wide strip lasers are used to increase the volume of the active material

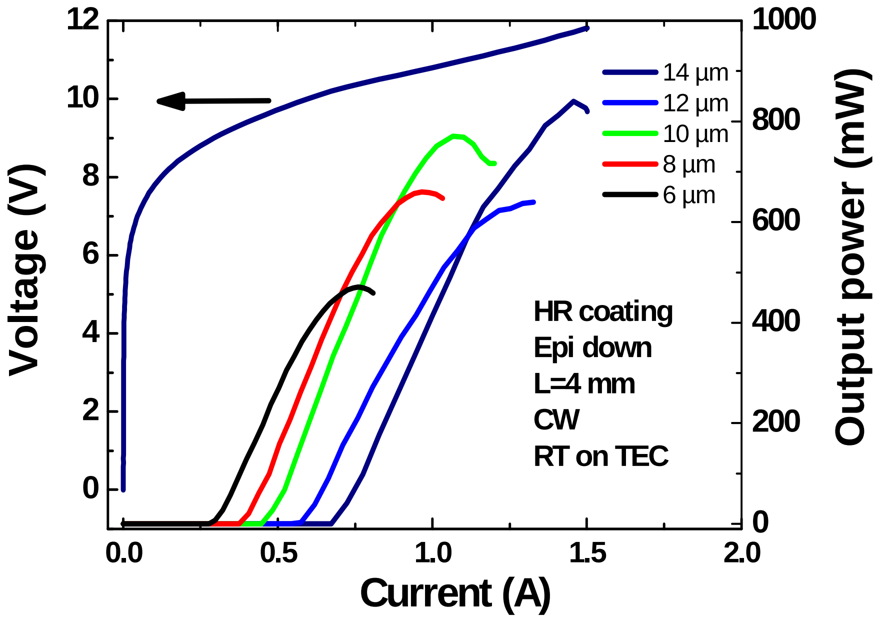


Y. Bai, et al., APL **95,** 221104 (2009)

High power QCLs with no Buried Het

- Au plated, HR coating and epi down mounting





Courtesy of X. Marcadet

III-V lab ALCATEL-THALES

List of companies providing QCL wafers, sources and sensor systems

Company name

1) AdTech Optics Inc.
2) Aerodyne Research Inc.
3) Alcatel-Thales III-V Lab
4) Alpes Lasers
5) Archcom Technology Inc.
6) Cascade Technologies
7) Daylight Solutions Inc.
8) Hamamatsu
9) IQE
10) Laser Components Inc.
11) Maxion Technologies Inc./PSI (Physical
12) Nanoplus Inc.
13) Neoplas Control Inc.
14) nLIGHT Corporation
15) Pranalytica Inc.
16) QuantaRed Technologies
17) Spire Corporation

AdTech optics

FP characterization for QCL device **# CS-HR17**

	Data	Comments
Cavity dim.	**12μm x 2 mm**	*Emitter width x length*
Submount dim.	**25x25x10 mm**	*Mounted epi-down on Cu – CS mount*
Oper. Temp.	**15 - 40C**	*All data at* 15C
Center wavelength	**4.72 μm**	*T=15C, cw*
Thresh. Current	**0.56 A**	*T=15C, cw*
Max. Current	**1.75 A**	*T=15C, cw*
Thresh. Voltage	**12.2 V**	*T=15C, cw*
Max. Voltage	**14.7 V**	*T=15C, cw*
Max Power out	**1.5 W**	*HR coated, single facet*
Max Efficiency	**5.8 %**	*Total power*

Applications

➔ **QC lasers are a mid infrared laser technology based on III-V *semiconductor* compounds such as GaAs and InP**

- **Spectroscopic applications (Gas, molecular detection)**

  Output power = 10mW, CW operation, control on the linewidth

  - **Medical**
  - **Environmental**
  - **In line quality control**
  - **Food storage**
  - **Security** *(Explosive detection)*

- **Optical countermeasure (High power devices)**

  Output power > 1W, CW operation non strictly necessary

  - **3-4µm for missile out-steering**
  - **8-10µm for night vision blinding**
  - **8-10µm furtive illumination system**

Quantum cascade lasers

Quantum cascade lasers are semiconductor devices based on III-V compounds materials with physical properties that differ fundamentally from those of diode lasers.

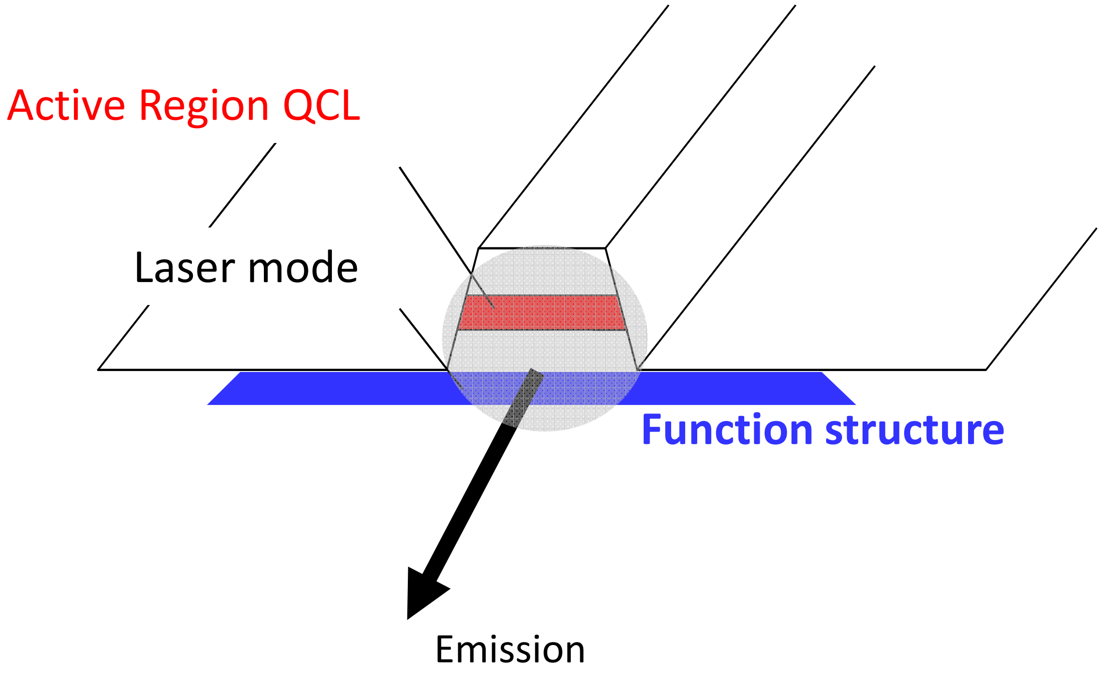
1) Unipolar devices based on Intersubband transition
2) Operate at very different wavelength (5 – 100 μm)

However fundamental physical differences have not been yet fully exploited:

- Gate contacts for carrier depletion
- Three terminal devices
- Parallel transport (acceleration of electron in the quantum well)
- Phonon engineering
- Photonic structures based on metal guiding
- Extremely short upper state life-time (Ultrafast modulation)

Three terminal devices for integrated functions

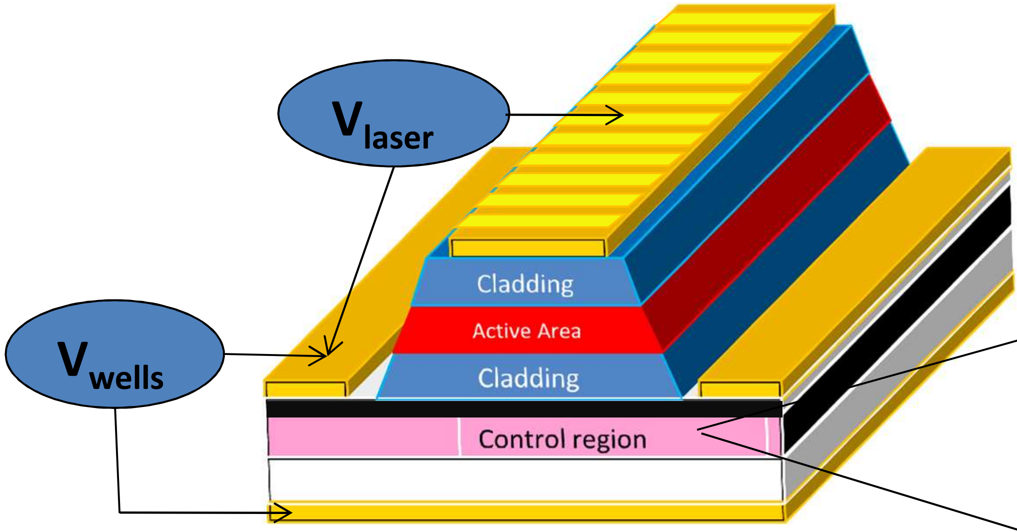
Integration of different functionalities



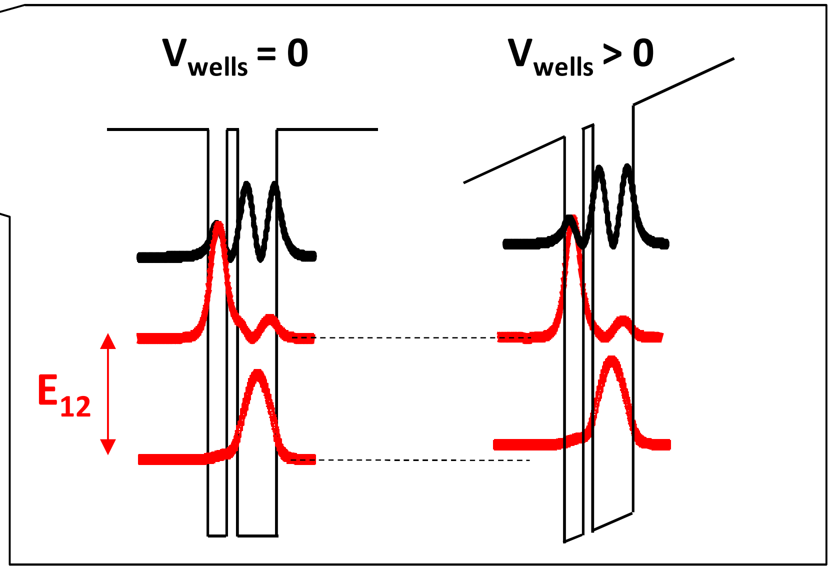
AM or FM modulator

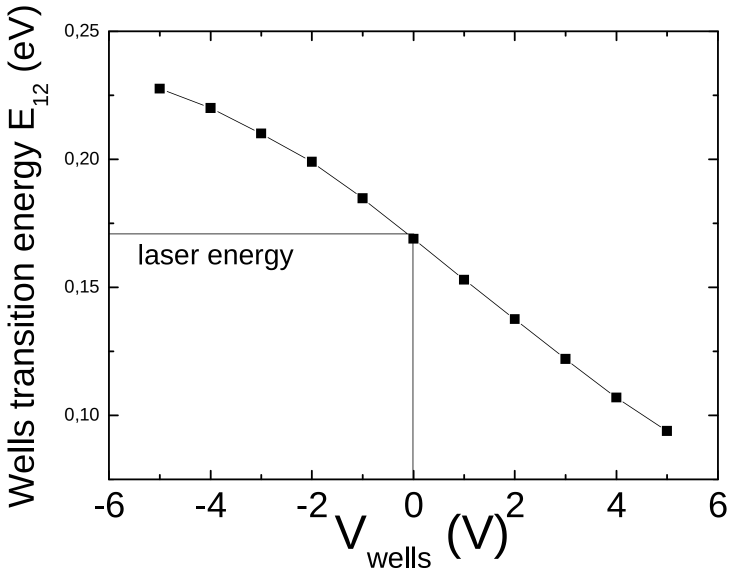
Pumping nonlinear structures

Three terminal devices: AM and FM of QCL



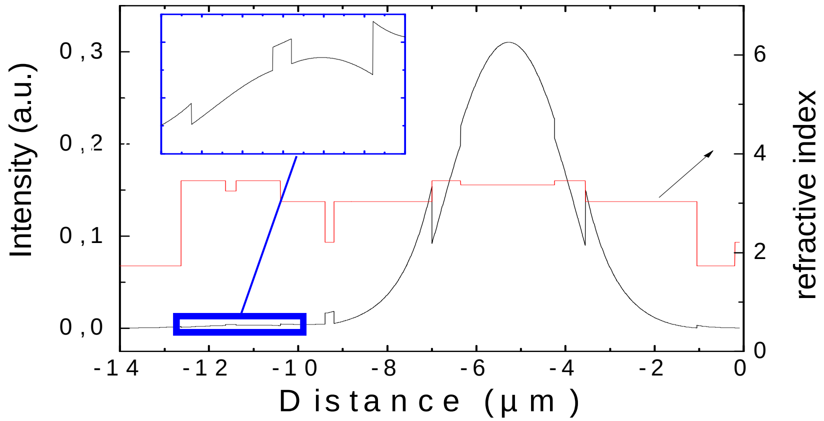
Addition of electrically tunable optical losses within the laser cavity

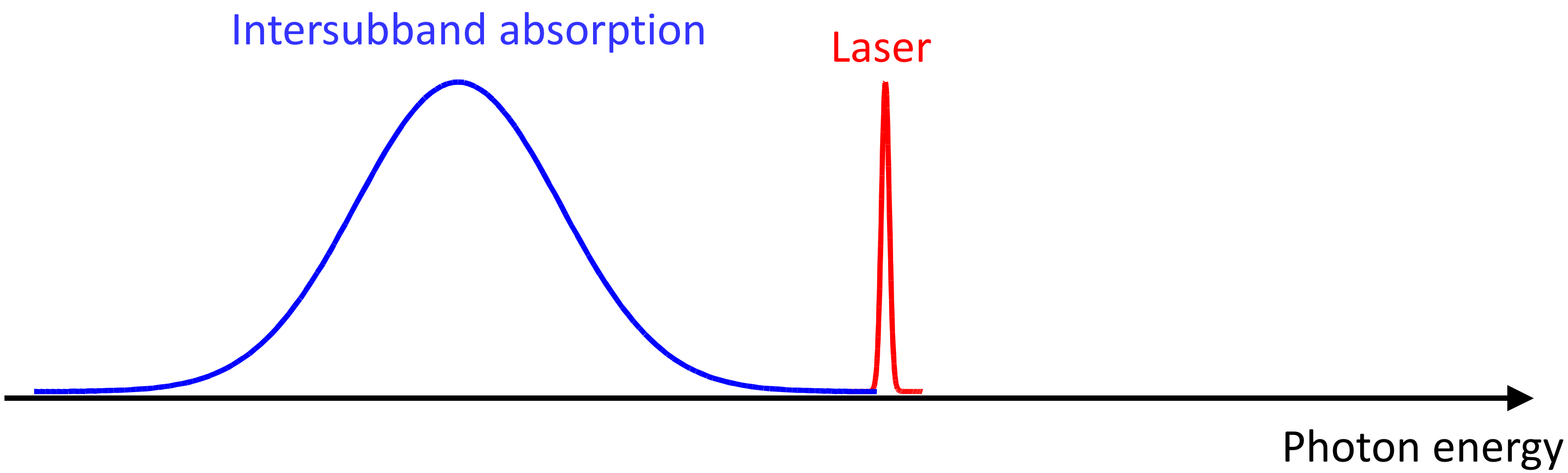




J. Teissier *et al*. APL 94, 211105 (2009)

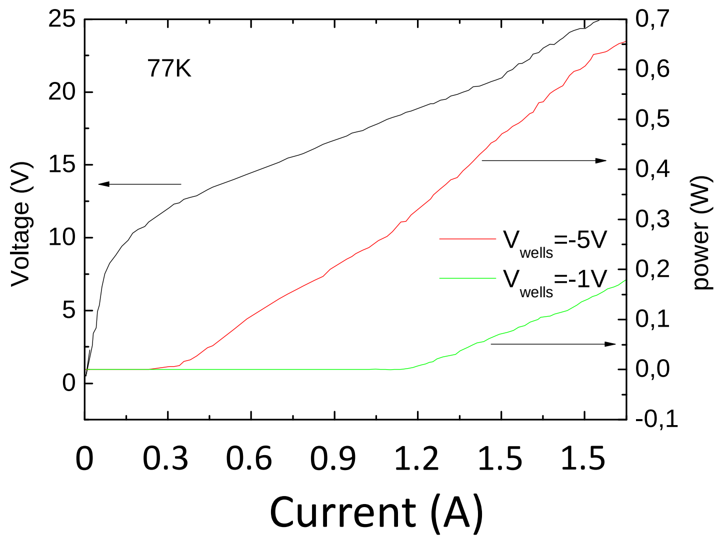
Amplitude and Frequency modualtion

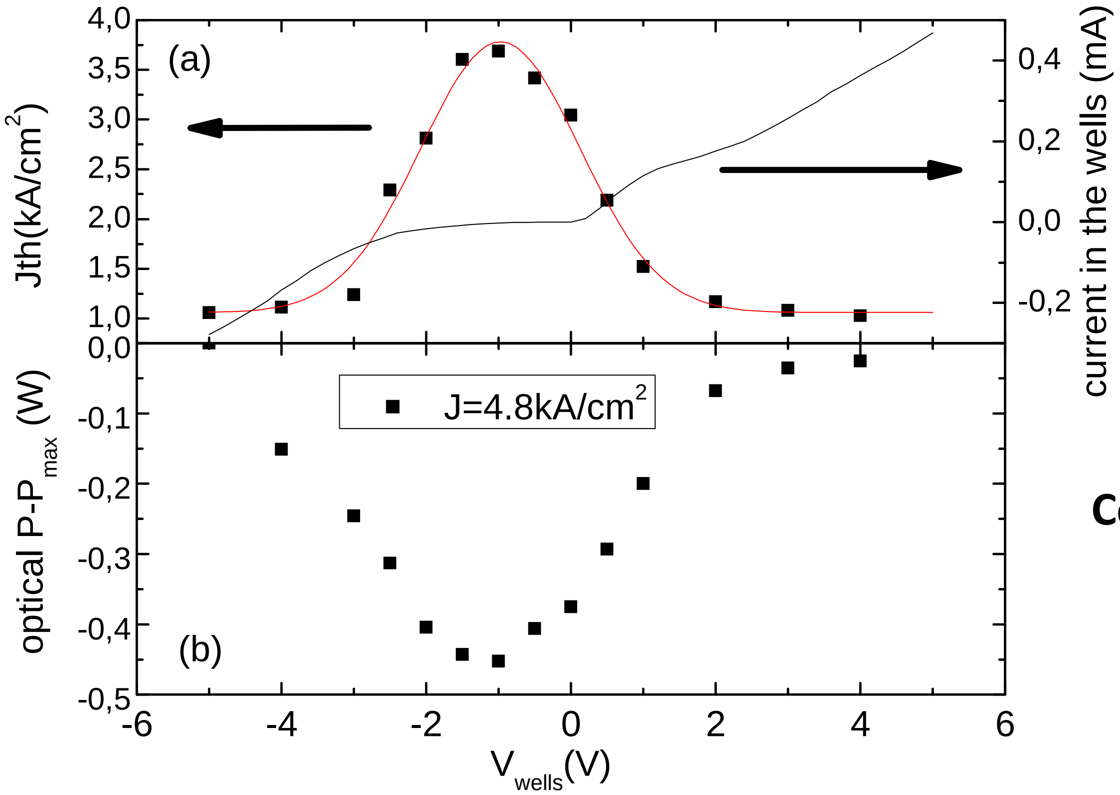




Amplitude and phase modulation of QCL

~0,45 W modulation depth with < 1mW of electrical power injected into the control region



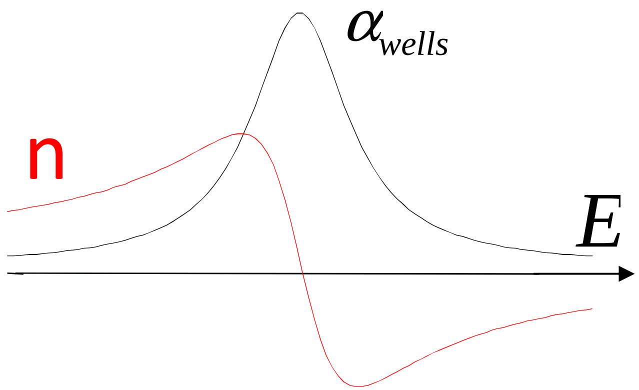


Could avoid linewidth enhancement at low modulation frequency

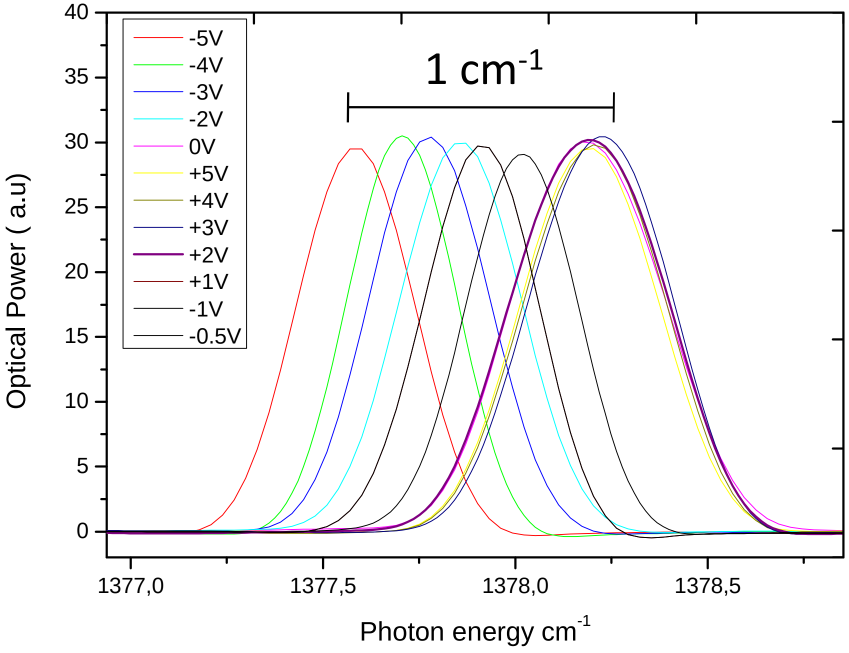
Wavelength tuning

Refractive index variation associated with the absorption feature

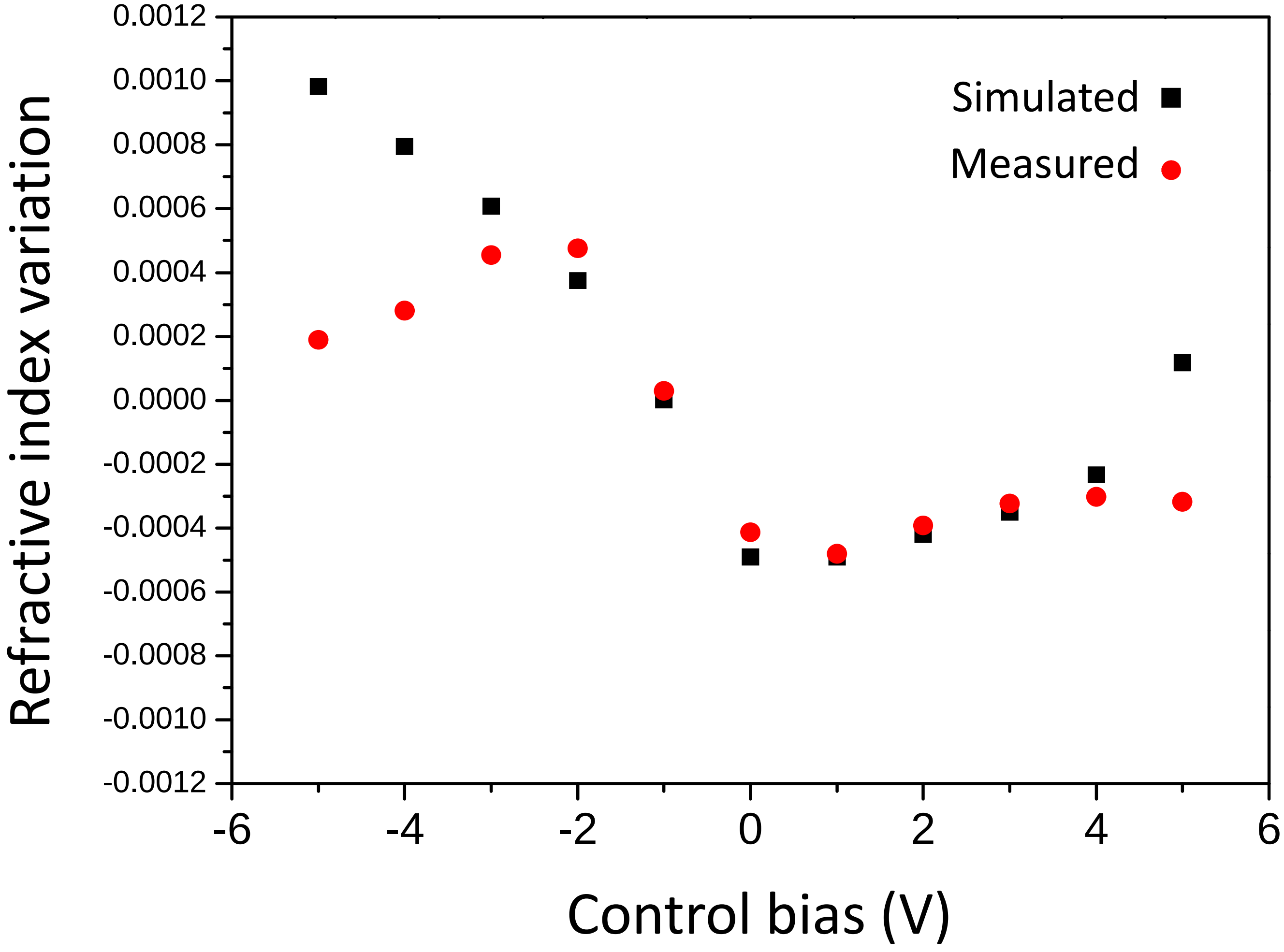
$$\lambda_{DFB} \sim 2n_{eff}\Lambda$$



Constant Optical Power by adjusting the current

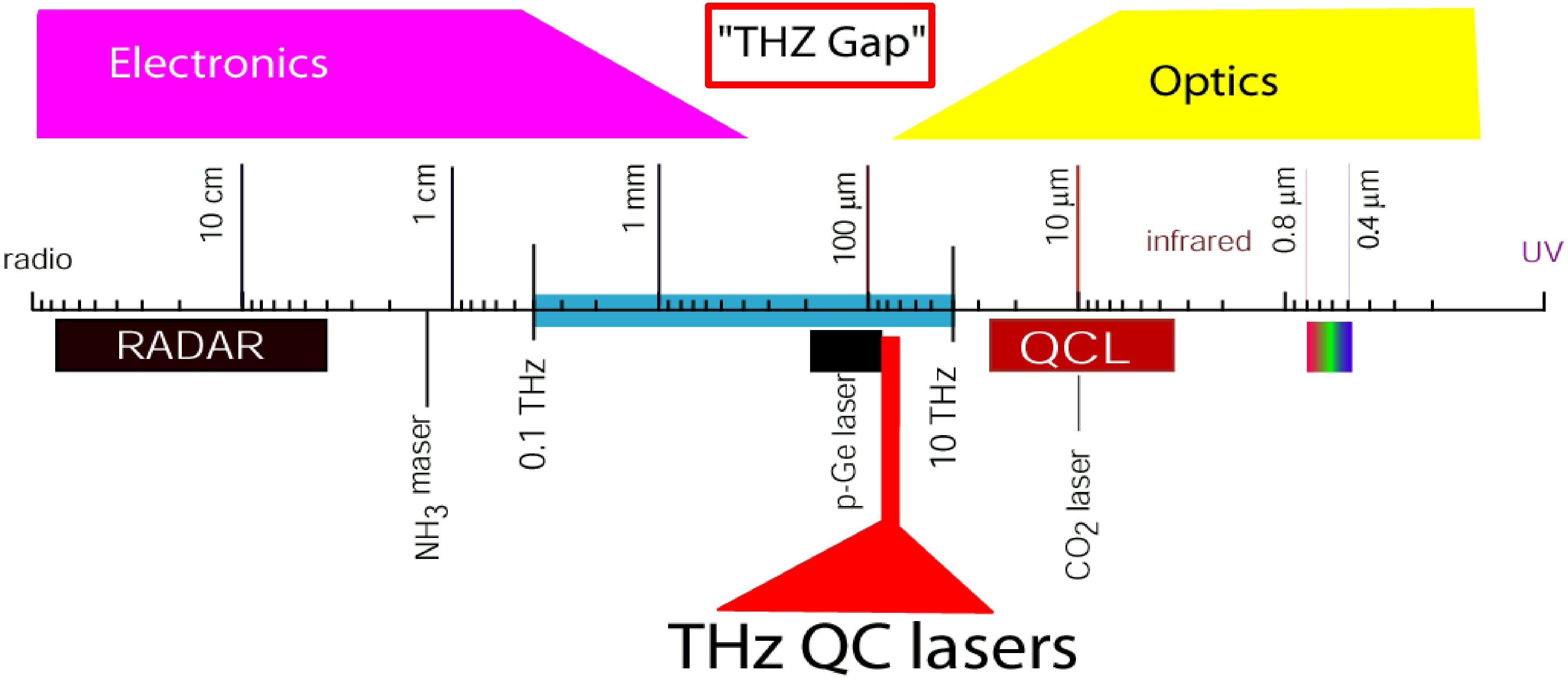


Rafrective index variation

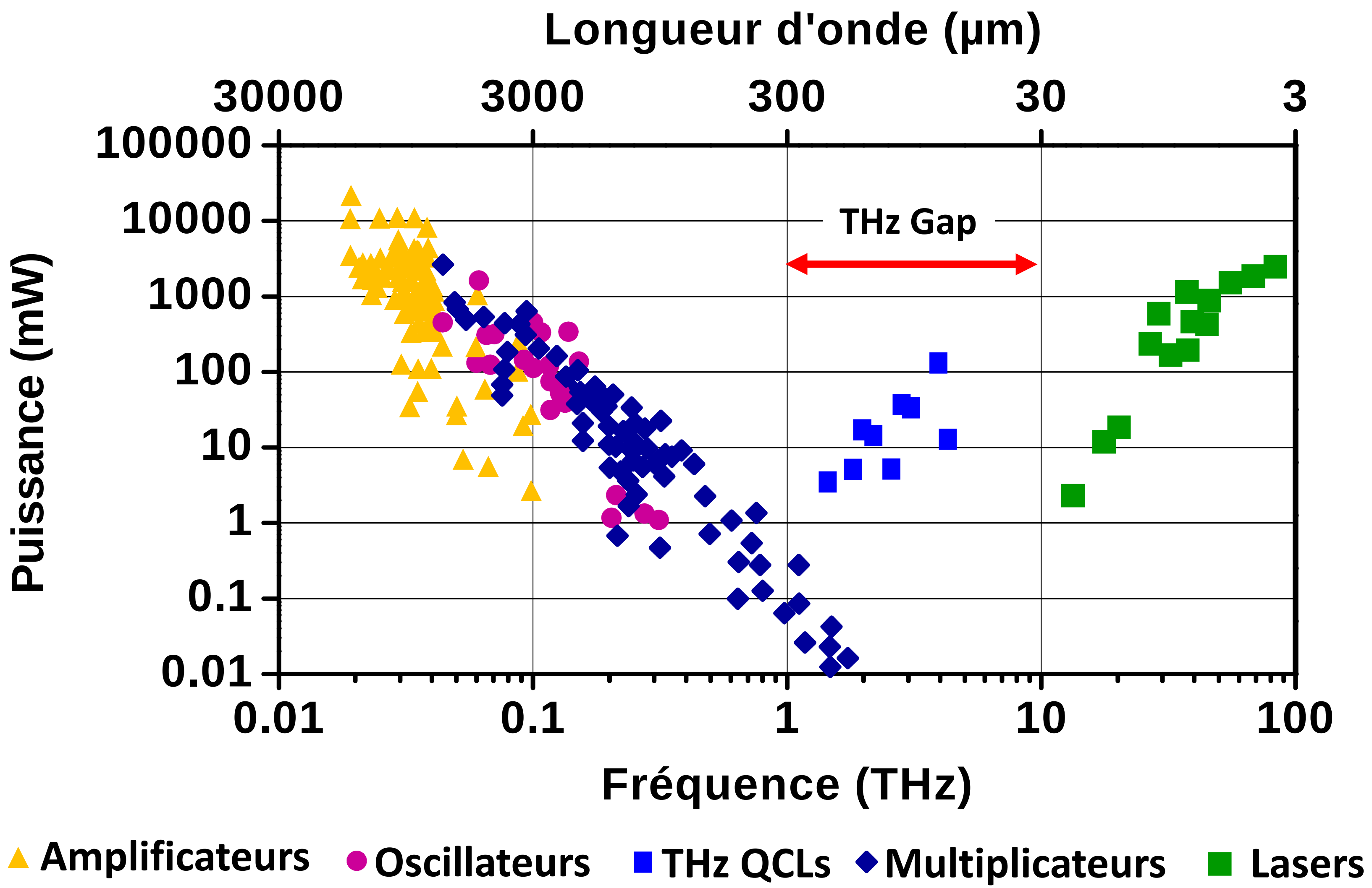


Quantum Cascade lasers
@ THz frequencies

1 THz =	300cm^{-1} =	4.1meV =	300μm
Frequency	Energy (cm^{-1})	Energy (meV)	Wavelength



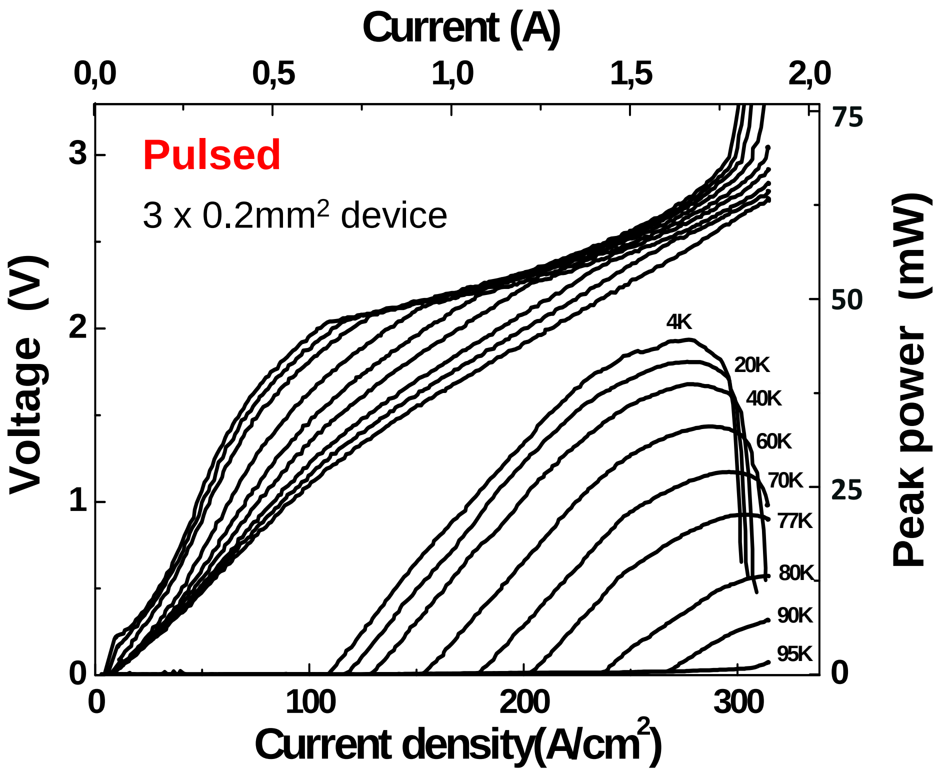
Applications: medical imaging, bio-sensing, communications

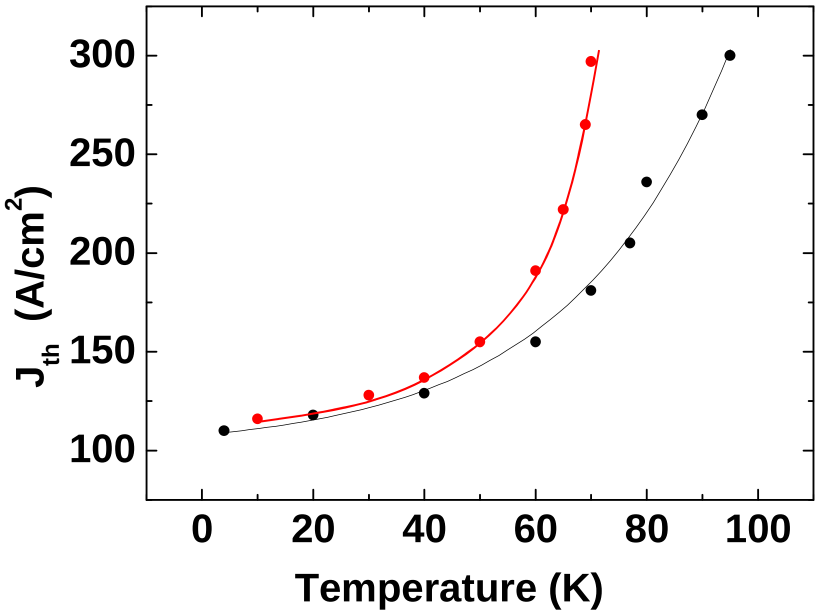


Longueur d'onde (μm)
30000
3000
300
30
3
100000
10000
1000
100
10
1
0.1
0.01
Puissance (mW)
THz Gap
0.01
0.1
1
10
100
Fréquence (THz)
Amplificateurs
Oscillateurs
THz QCLs
Multiplicateurs
Lasers

Performances of a 3THz QC laser

- T_{max} = 96K(pulsed); 70K(cw)





- 2% peak wall-plug efficiency at 4K
- 0.4% wall-plug efficiency in CW

S. Barbieri et al., APL (2004)

THz QCL main challenge: T_{max} Operation

Operation of terahertz quantum-cascade lasers at 164 K in pulsed mode and at 117 K in continuous-wave mode

Benjamin S. Williams, Sushil Kumar, and Qing Hu
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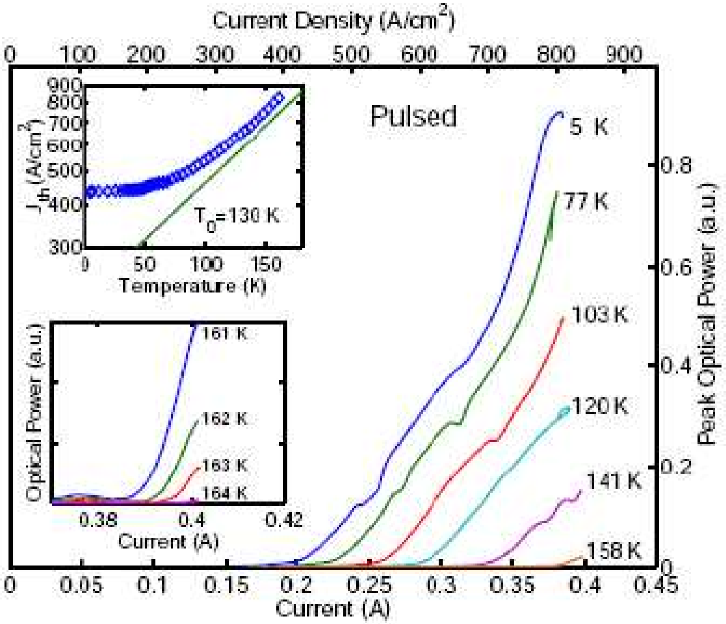
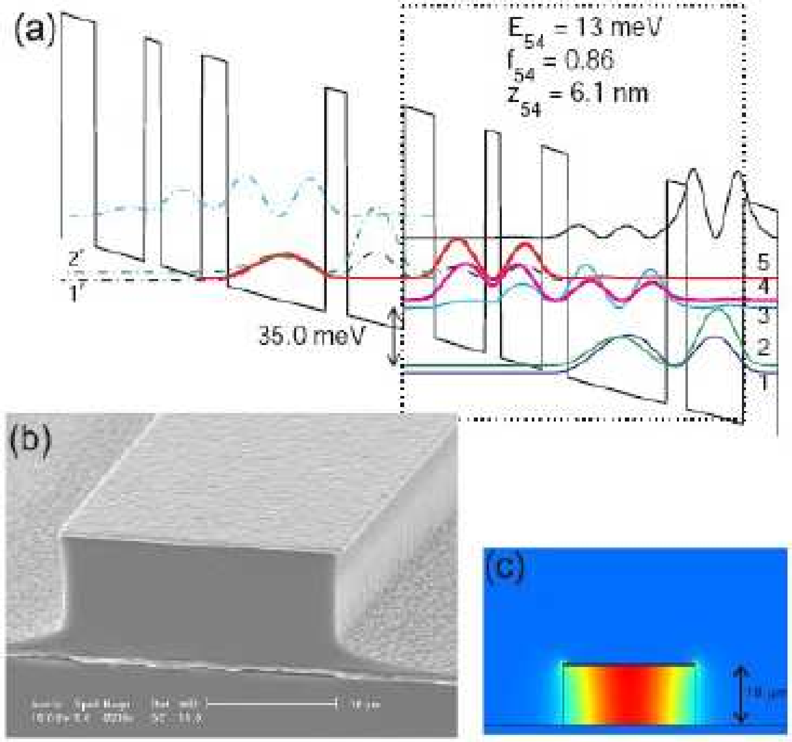
qhu@mit.edu

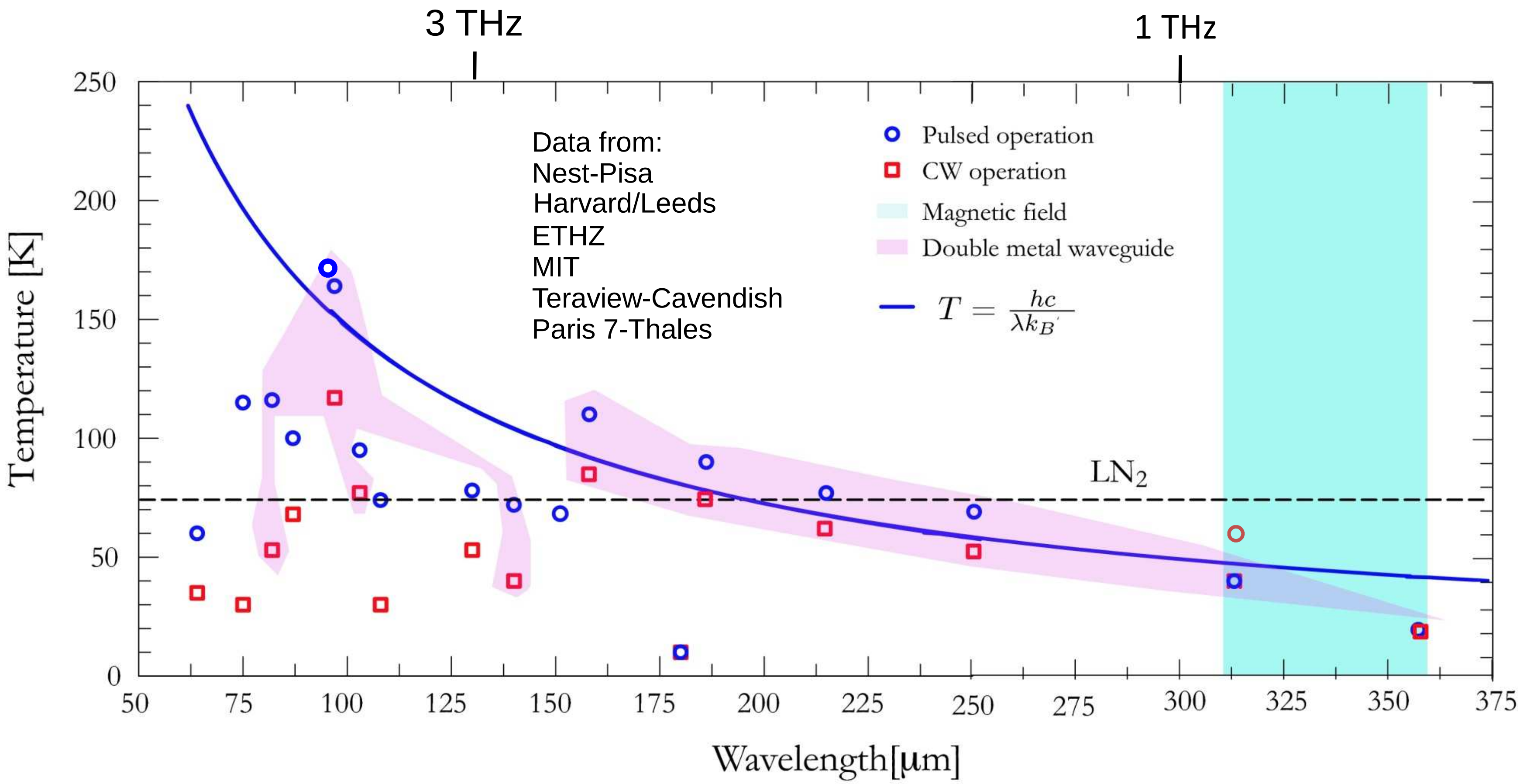
John L. Reno
Sandia National Laboratories, Dept 1123, MS 0601, Albuquerque, New Mexico 871...

Balkin et al. APL 2008
T_{max} = 178K





Terahertz QCLs performance vs. wavelength



Courtesy of G. Scalari, ETHZ

Metal guiding

Metal guiding

In the mid infrared quantum cascade lasers have imported **material**, **processing** and device **architecture** from the well know III-V platform for diode lasers

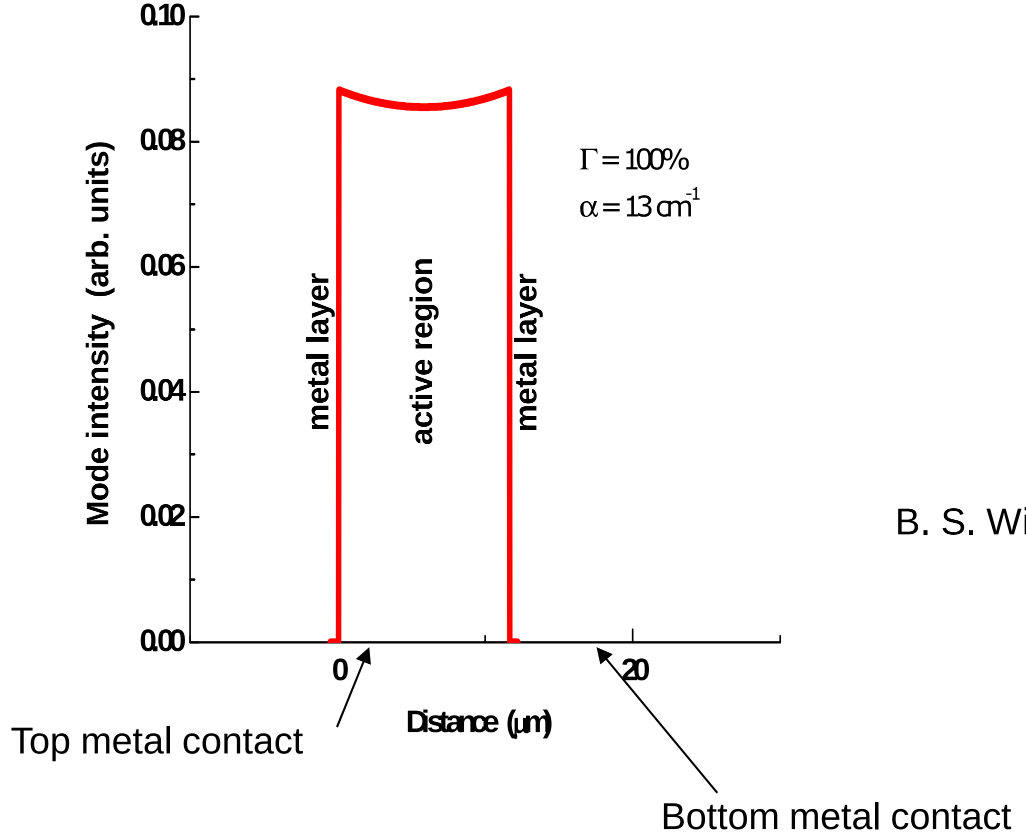
This has allowed to produce rapidly high performance devices.

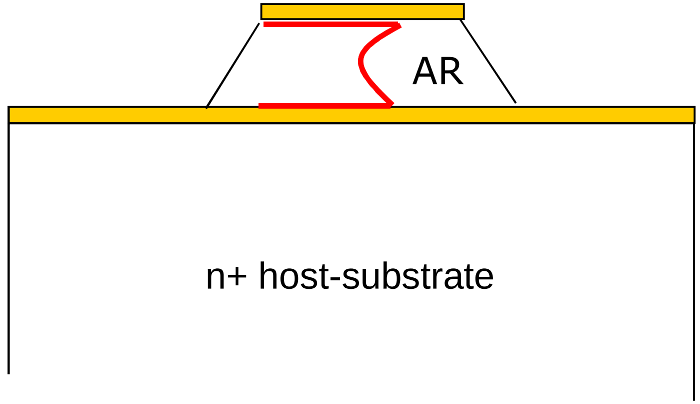
However in the THz region this is not possible because of the scaling of the dimensions with the wavelength

Ideas and concepts and have been imported from the other side of the spectrum: in the microwave region.

The optical guiding has been developed using metal-metal structures as for *microwave strips*

Double-metal waveguide



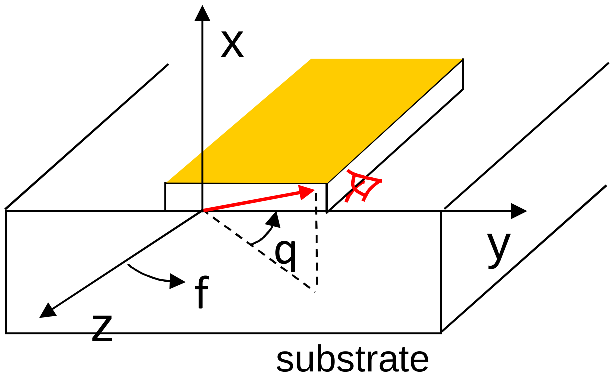


B. S. Williams *et al.*, Appl. Phys. Lett, vol. 83, 5143 (2003)

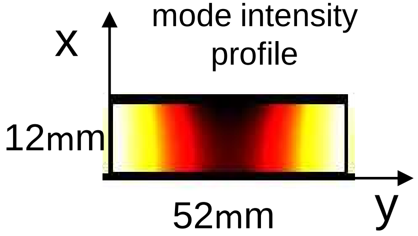
Advantage:
Overlap factor 100%, independent from l and doping; strong lateral confinement

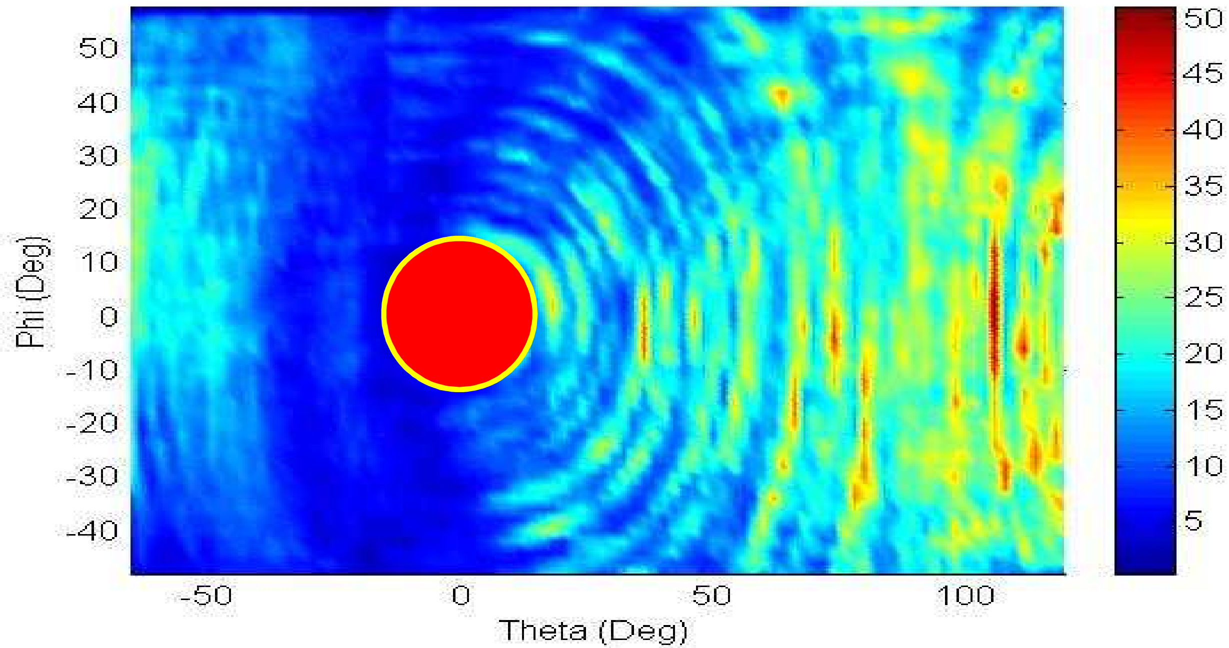
Drawback:
Low out-coupling (R > 0.9); More difficult fabrication

Far field of a metal-metal QC THz laser



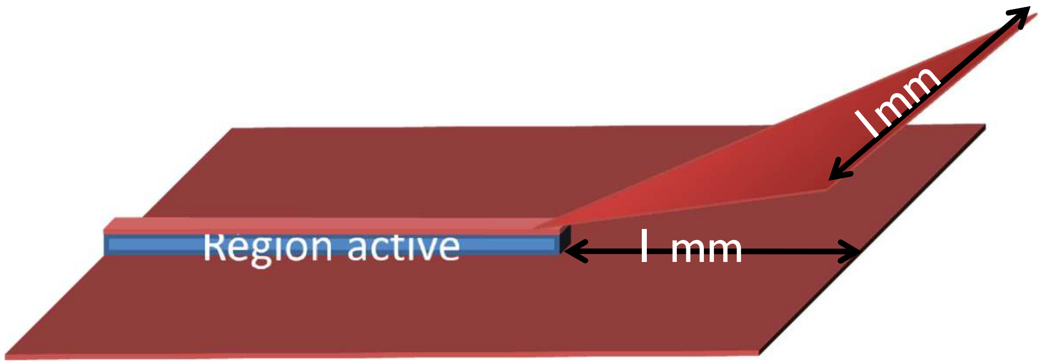
Metal-metal devices

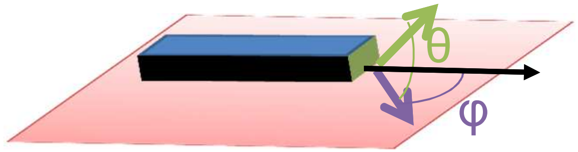


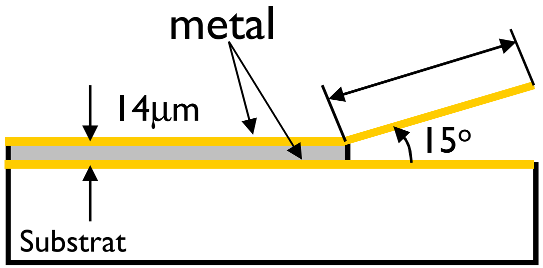


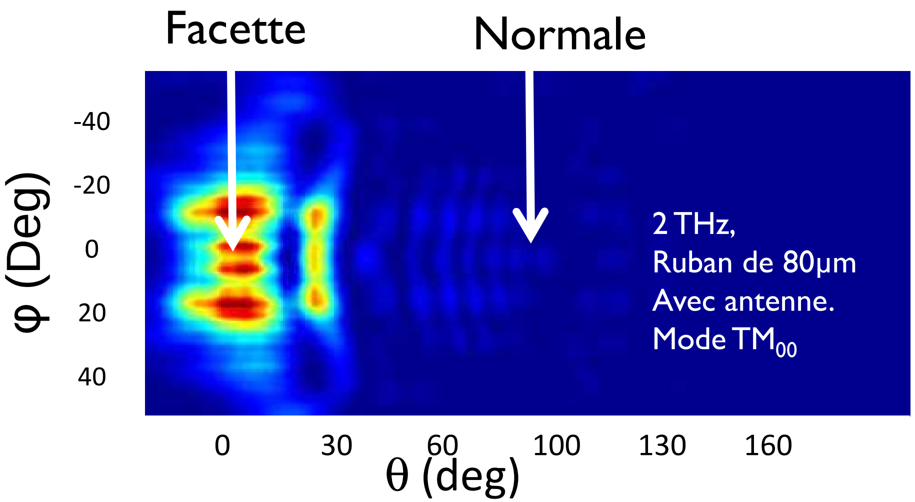
The strong interaction between the guided mode and the metal excite the top contact which act as an antenna

Horn antenna







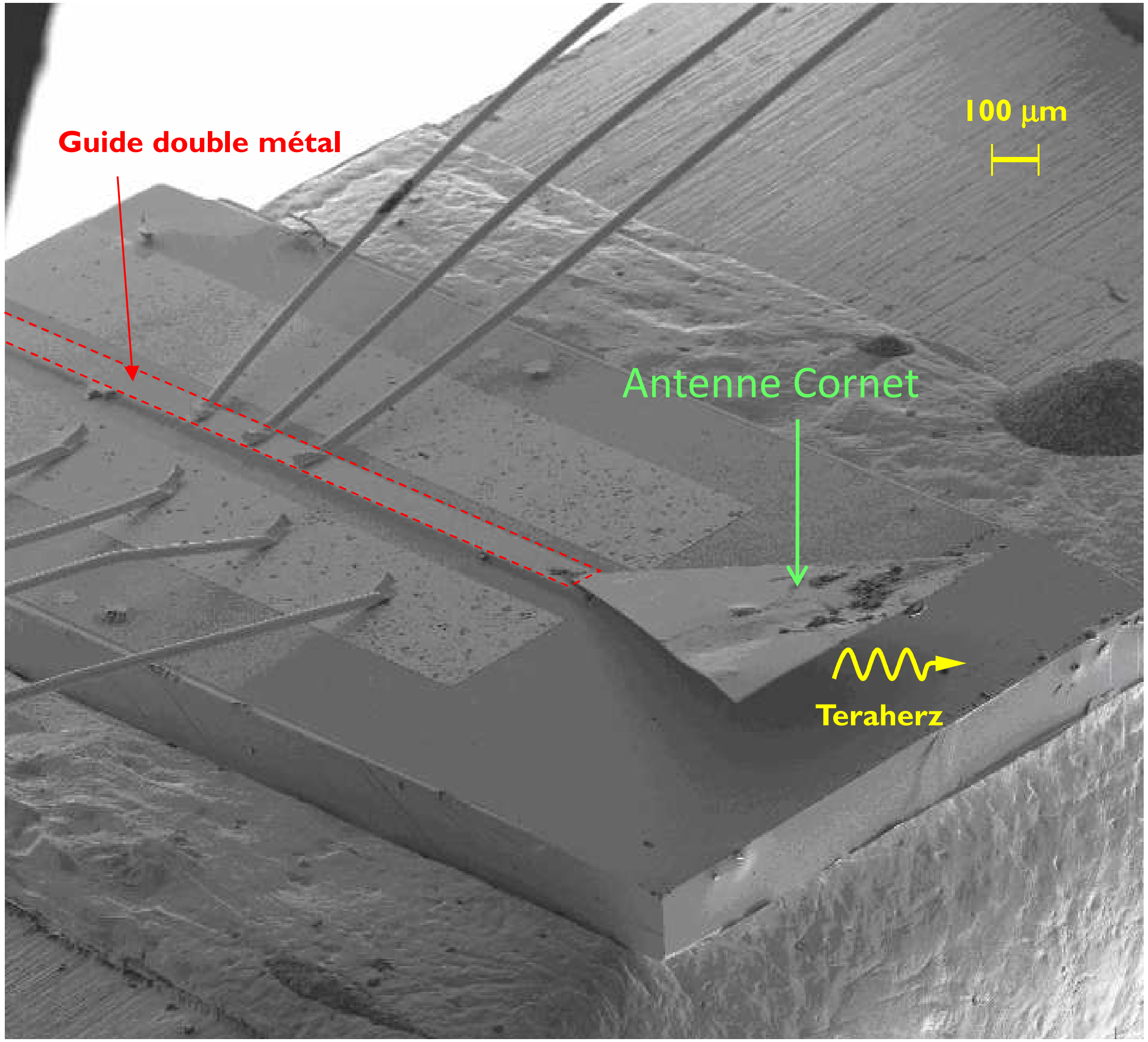


Impédance du guide DM ≈ 20 Ω

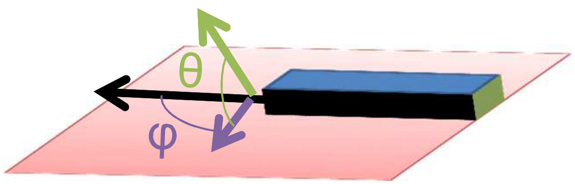
Impédance de l'antenne: ≈ 50 Ω

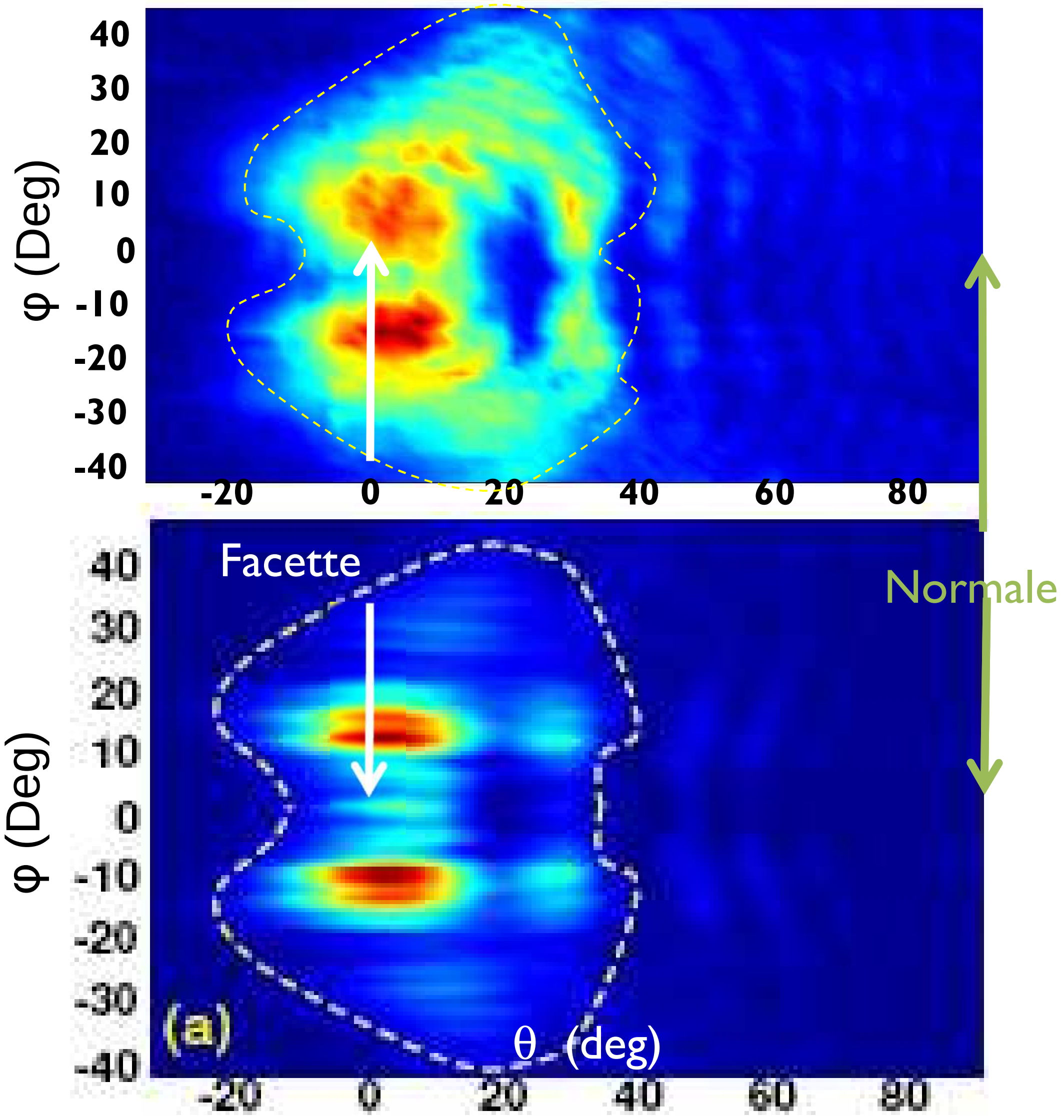
Impédance du vide: 377 Ω

QC laser with horn antenna



Résultats expérimentaux : laser de 41 µm de largeur muni d'une antenne cornet





Maineult and al., APL 93, 183508 (2008)

Phase-locking of a 2.7 THz QC laser to a mode-locked Er-fiber laser

Nature Photonics 1, 411 (2007)

ARTICLES

Terahertz transfer onto a telecom optical carrier

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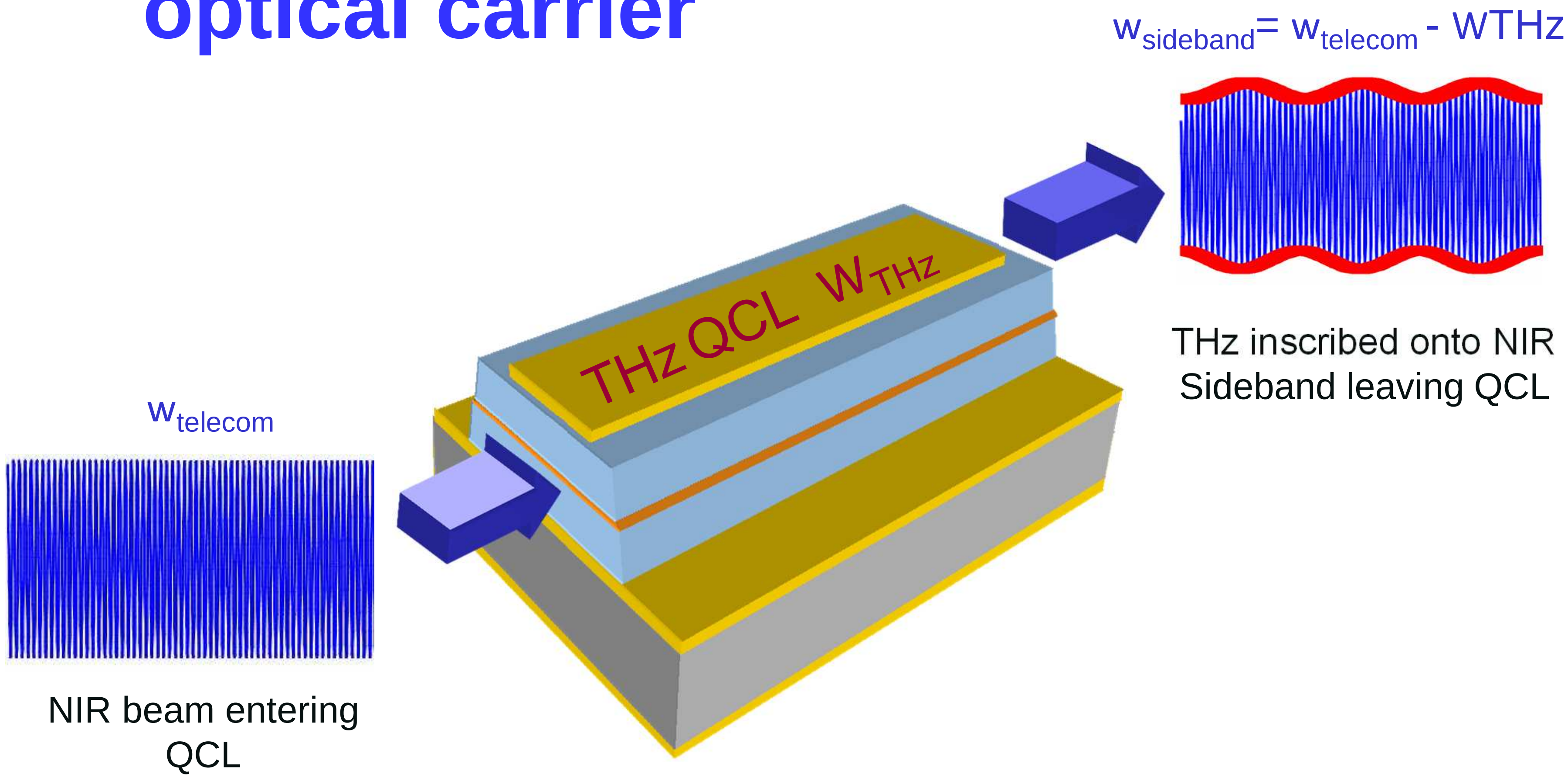
1 Matériaux et Phénomènes Quantiques, Université Paris 7, 10 rue A. Domont et L. Duquet, 75205 Paris Cedex 13, France
2 Teraview Ltd, St John's Business Park, Cambridge, CB4 0WS, UK
3 Thales Research and Technology, Route Départementale 128, 91767 Palaiseau Cedex, France
4 Cavendish Laboratory, University of Cambridge, Madingley Rd, Cambridge, CB3 0HE, UK

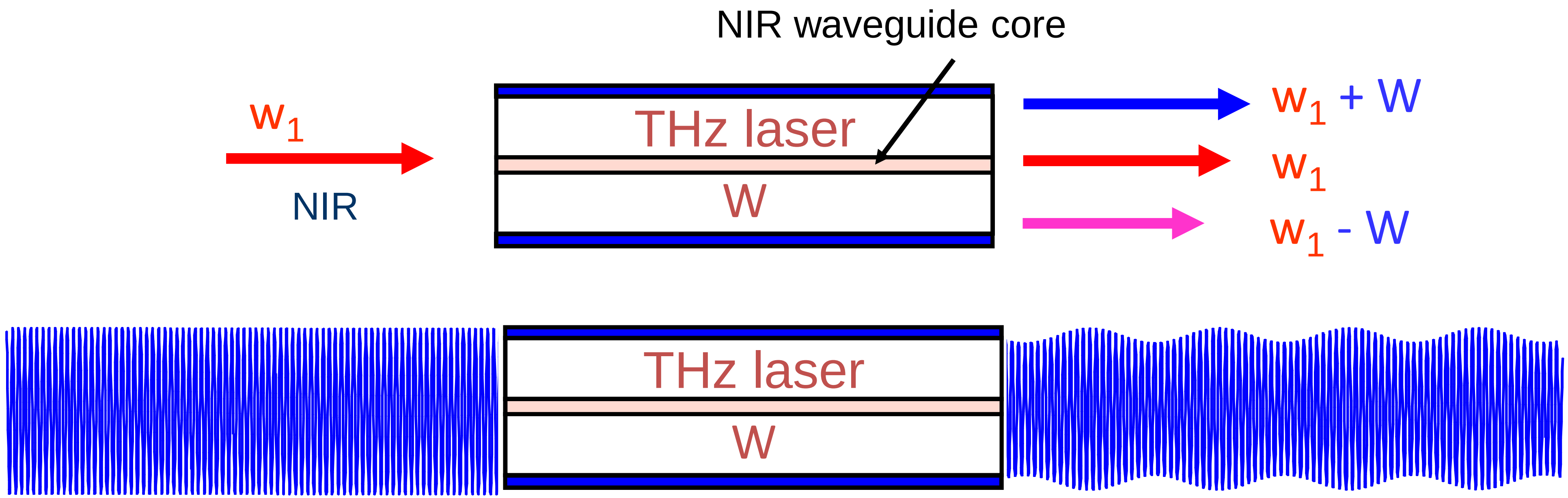
THz transfer on an optical carrier



The THz QCL is both the THz source and non-linear medium

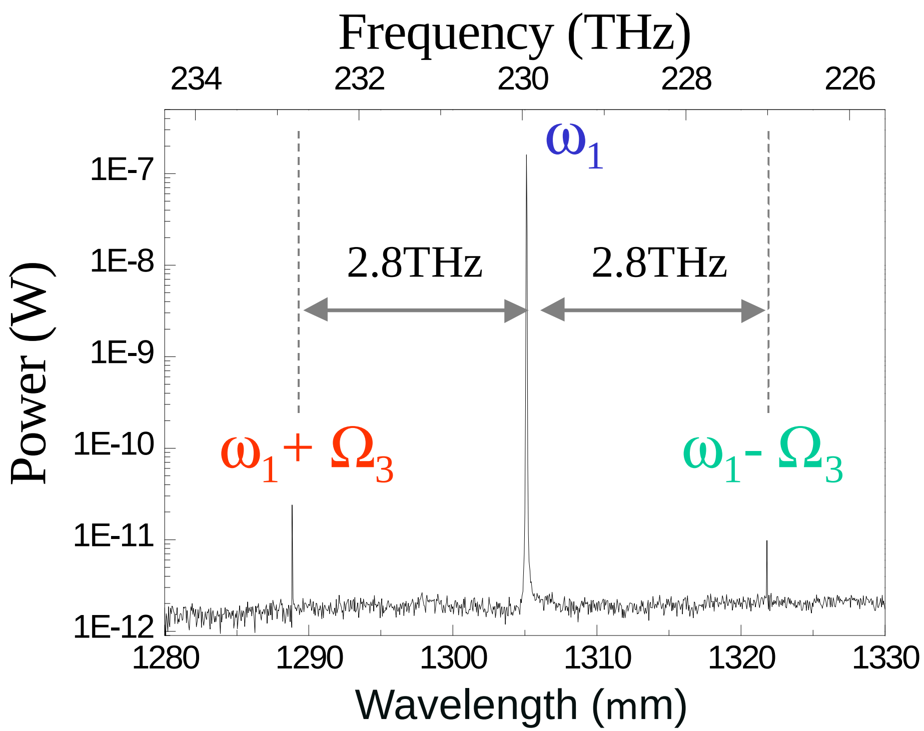
THz side band generation

at telecom frequencies



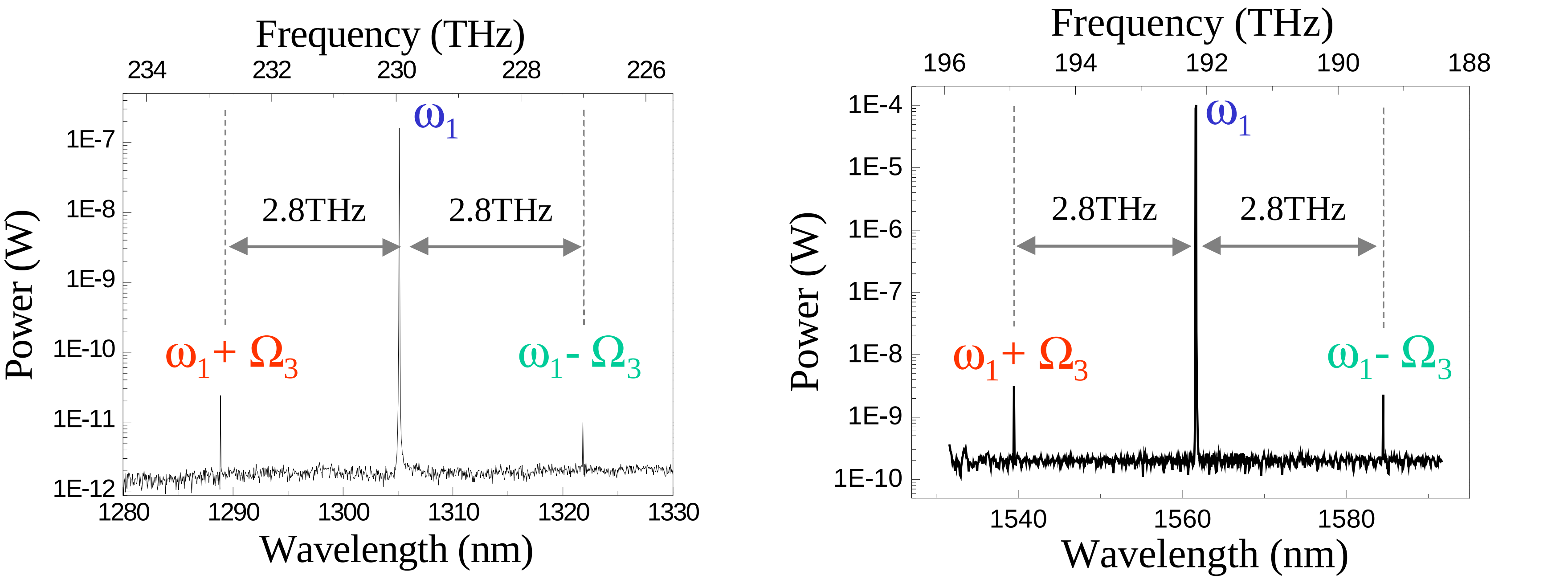
THz QCL is both the THz source and non-linear medium

THz side band generation
at telecom frequencies



- THz up-conversion to N-IR wavelength!
- Modulation of a telecom beam at THz frequencies
- Transmission of THz through optical fibre

THz side band generation @ 1.3mm and 1.5mm



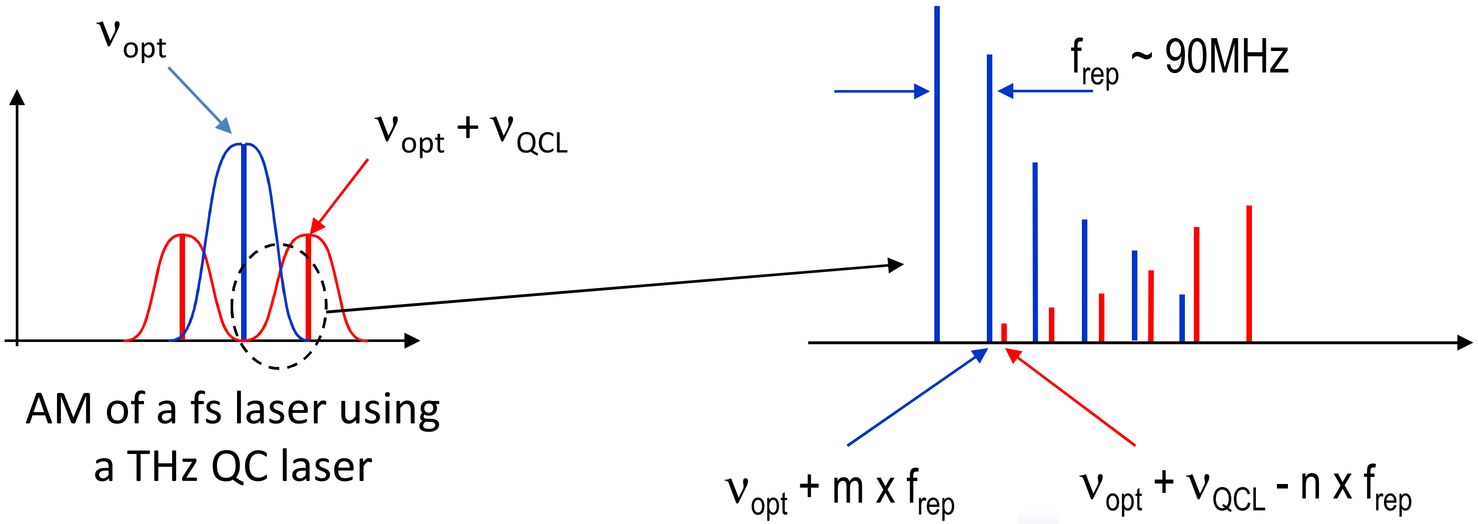
Typical NIR input power 100mW – 1mW

By injecting 100mW of power → ~ 1mW on the sidebands

S. Dhillon et al. APL (2005)

S. Dhillon et al. Nature Photonics (2007)

Phase Locking of a THz QCL to a fs-fibre laser

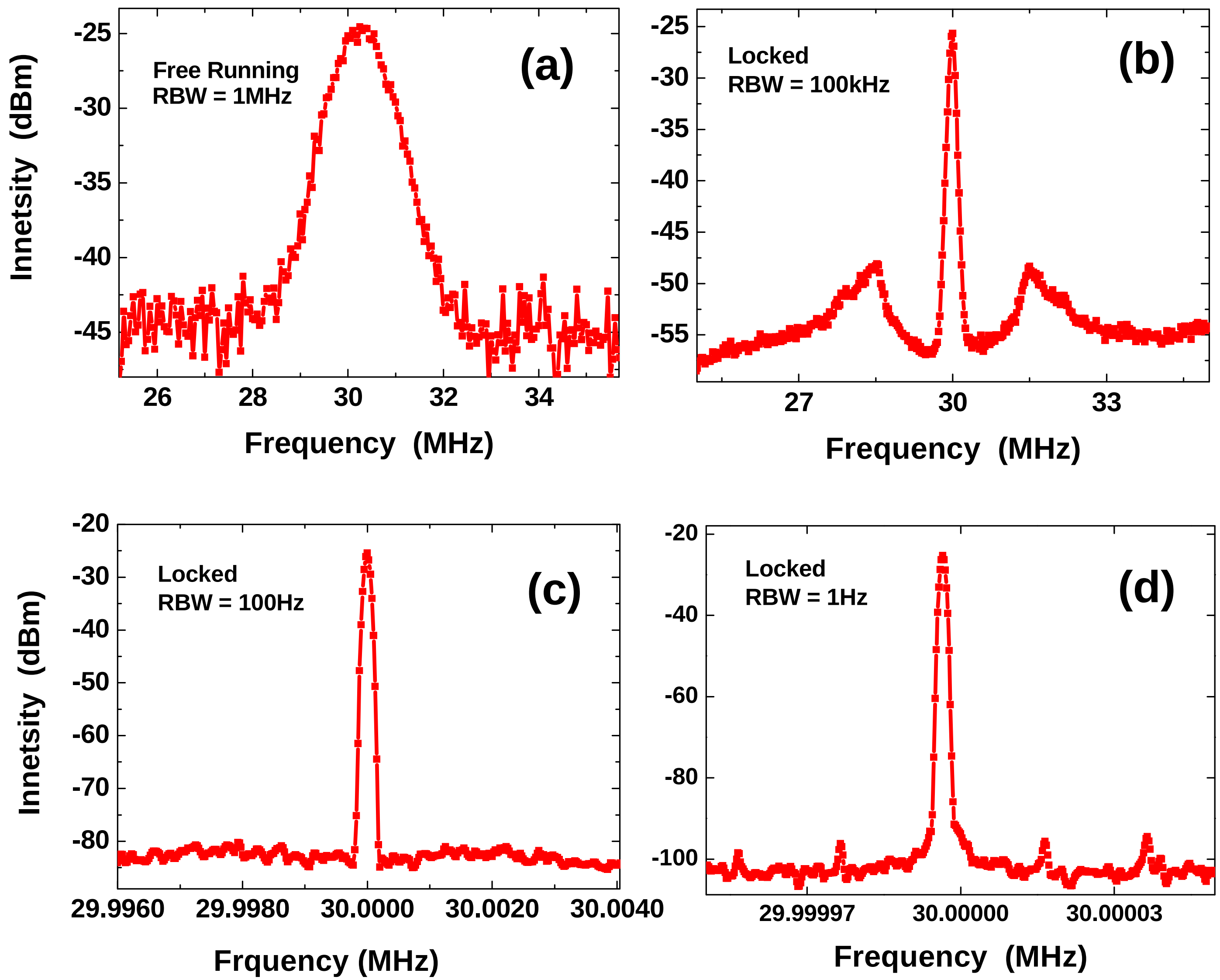


$$\delta f = (\nu_{opt} + \nu_{QCL} - n \times f_{rep}) - (\nu_{opt} + m \times f_{rep}) = \boxed{\nu_{QCL} - (n + m) f_{rep}}$$

- Suppression of ν_{opt} → The ultimate stability is given by f_{REP} (~90MHz)
- THz → MHz coherent link

See for example: A. Amy-Klein, *et al. Opt. Lett.* 30, 3320 (2005)

RF spectra of the beat-note signals vs RBW



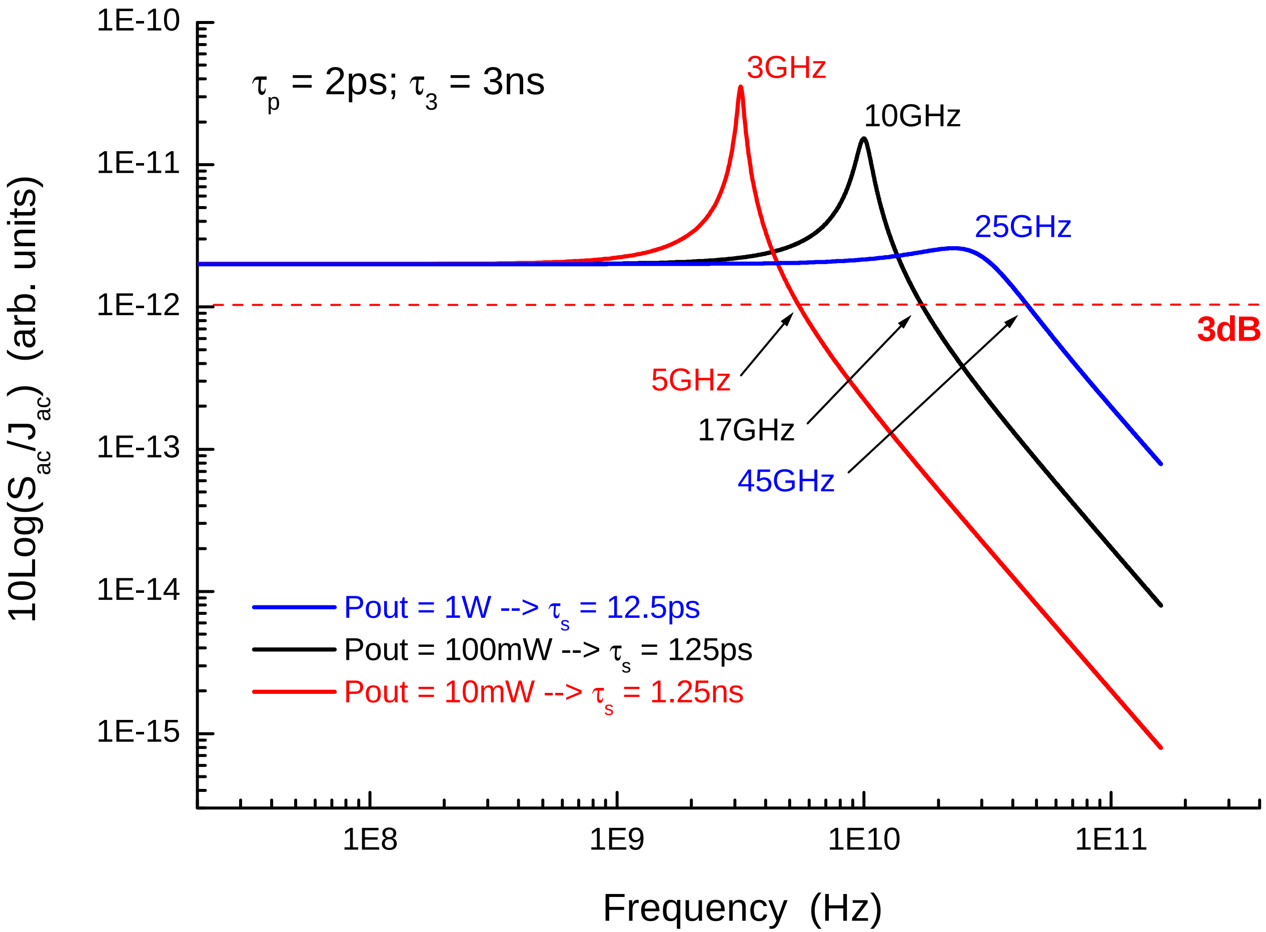
S. Barbieri, *et al.*, Nature Photonics (2010)

Ultrafast unipolar optoelectronics

Frequency response function of a diode laser

- $\tau_3 >> \tau_s > \tau_p$

τ_3 ~ 1ns



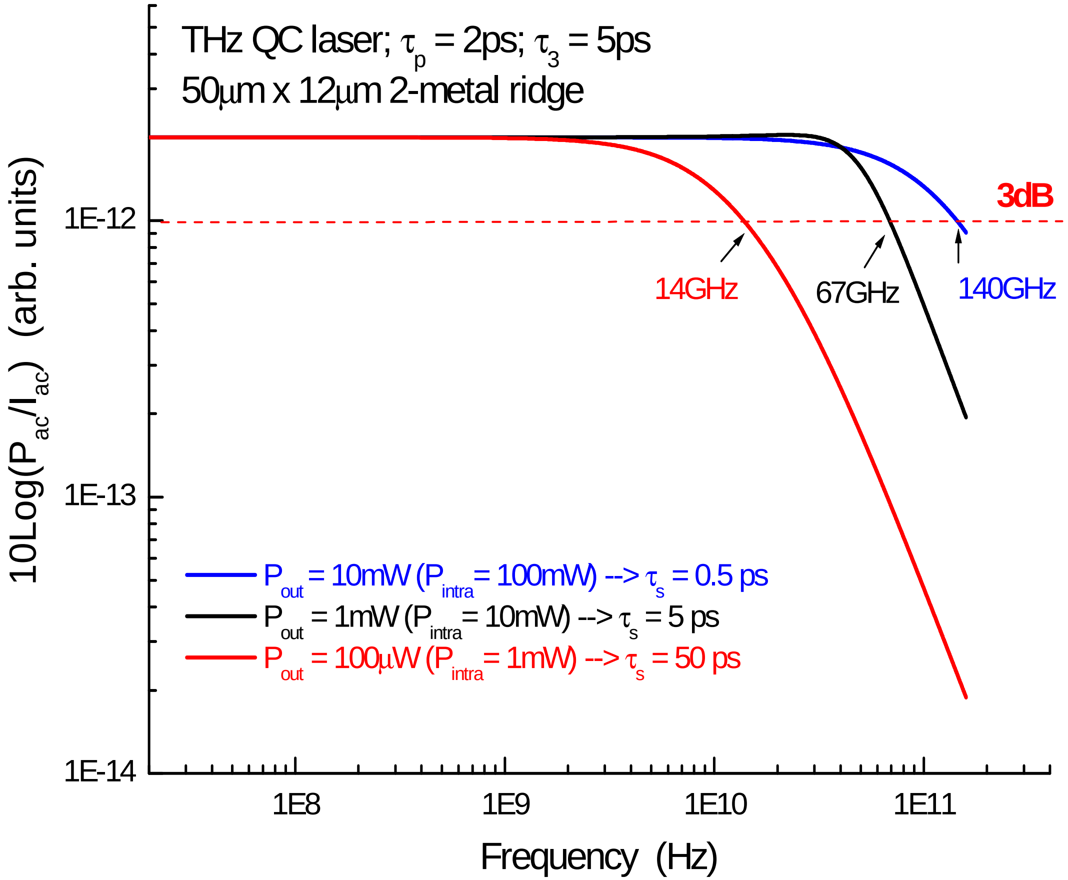
Frequency response function of QC lasers

➔ **Short non-radiative lifetime ~ 1ps ➔ no relaxation oscillations!**

The system acts as an over-dumped oscillator: the equilibrium of carrier population is restored within a round photon round trip

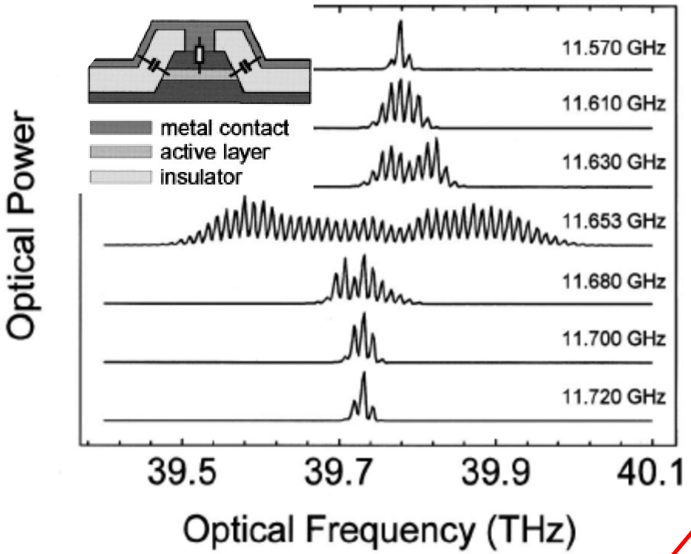
➔ **Short stimulated lifetime ~ 1ps ➔ very wide band of modulation**

The cascade enhance the number of photon in the cavity



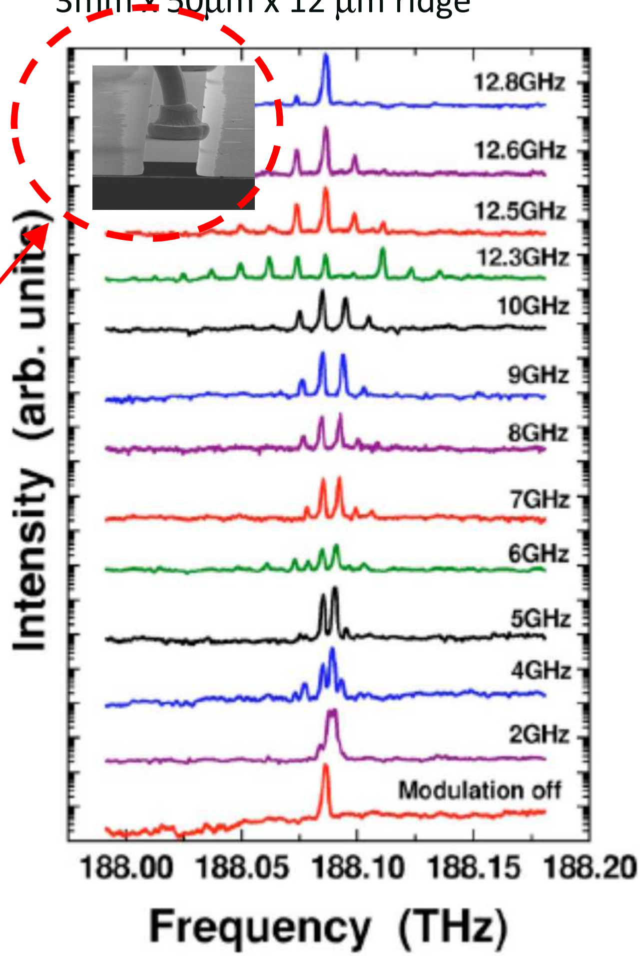
Results on QCLs RF modulation

8.1μm QCL
3.75 mm x 4.5 μm ridge with chalcogenide glass insulation layer to reduce device capacitance



R. Paiella et al., Appl. Phys. Lett. 77, 169 (2000)

Double metal QCL; f=2.9THz
3mm x 50μm x 12 μm ridge

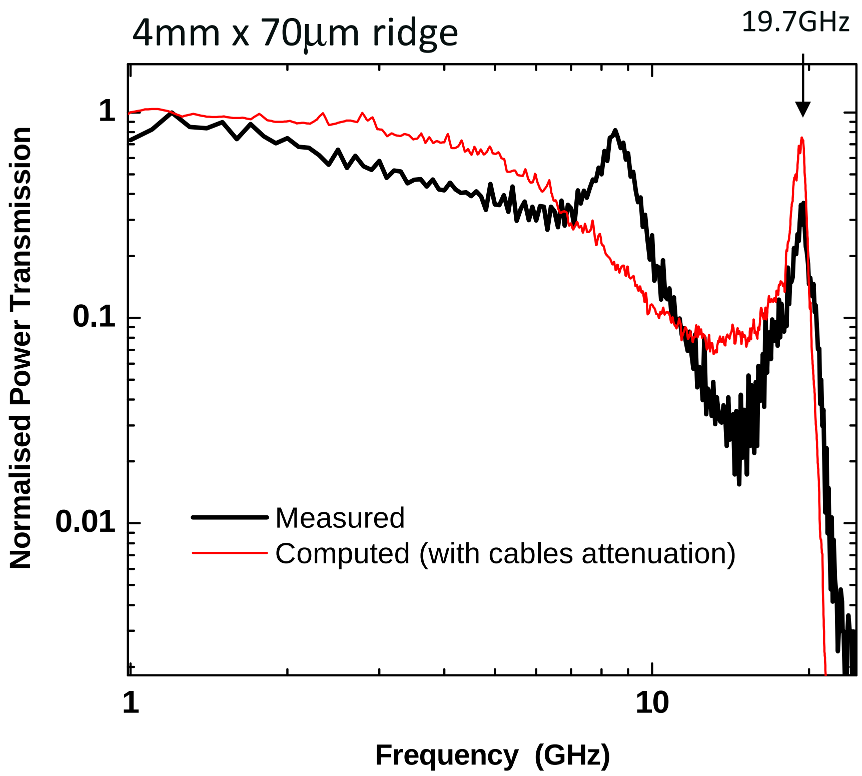


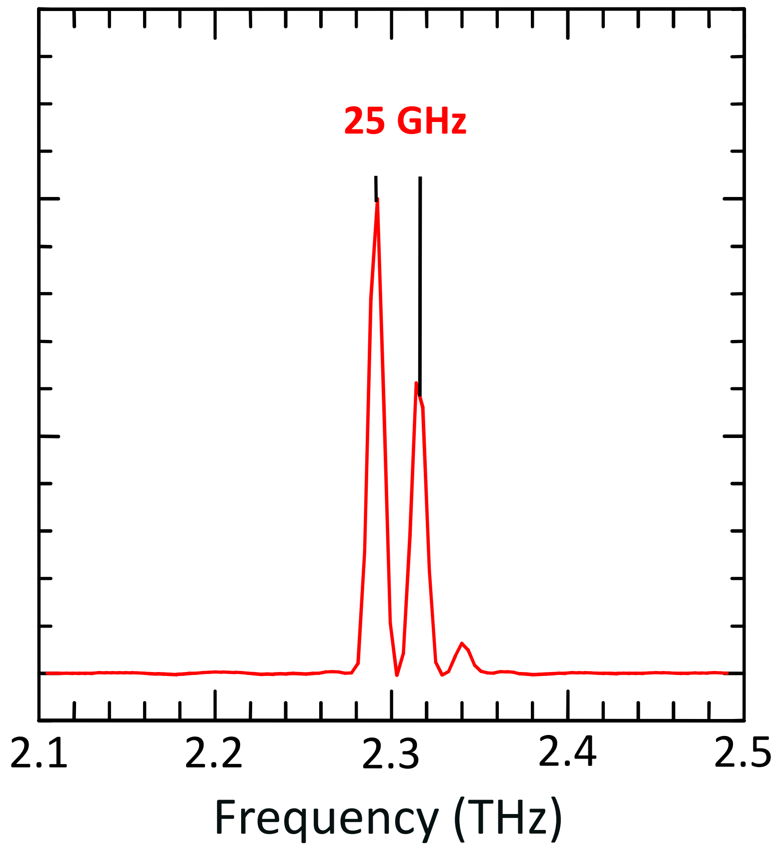
S. Barbieri et al., Appl. Phys. Lett. 91, 143510 (2007)

Double-metal waveguide allow for a low parasitic capacitance without any additional processing → High f modulation limited by wire-bond inductance

Modulation at 21GHz

- Narrow-band impedance adaptation





Spectra measured with up-conversion technique (res. 100MHz)

S. Dhillon et al., Nature Phot. 94, (2007)
S. Barbieri et al., Appl. Phys. Lett. 91, 143510 (2007)

Conclusions

- QC lasers are a technology based on III-V semiconductor compounds
- Semiconductor lasers can be fabricated in 3 – 300µm region using the same physical principles
- QC THz lasers are the only semiconductor solutions the 2 – 6 THz range
- QC lasers are a field of research in connection with the industrial world.
- QC lasers are a field of research in connection with the industrial world :
  - Opportunity to develop new ideas and intellectual property
  - Engineering of integrated new functionality
  - Merging QC lasers with other important technologies as: µ-wave, telecom, femto second fibre lasers