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**2443-24**

**Winter College on Optics: Trends in Laser Development and Multidisciplinary Applications to Science and Industry**

***4 - 15 February 2013***

# Mid-Infrared Lasers and Applications

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# Mid-Infrared Lasers and Applications

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# Summary

- Introduction to Mid-InfraRed (MIR) wavelength interval
    - (MIR: 3 micron – 25 micron)

- MIR sources (soild state)
    - Parametric devices
    - Solid-State lasers (bulk and fibre Lasers)

- Quantum-cascaded Lasers (QCL)
    - Introduction
    - State-of the art

- Conclusions

# Mid-InfraRed wavelength interval

MIR Sources (3-25 micron) are of great interest are absorbed by vibrational transitions

The MIR abpsorbtion spectra is therefore related to the specimen structure (3D) and the absorbed energy is in the range of “thermal” energy (phonons).

This allows

Unique recognisation of chemical specimens (e.g. pollutants) or 3D structures (e.g. cancer tissue vs. health tissue).

Possibility to follow structural modification

Microsurgery and *in vivo* investigations.

# Mid-InfraRed wavelength interval

*What is available*

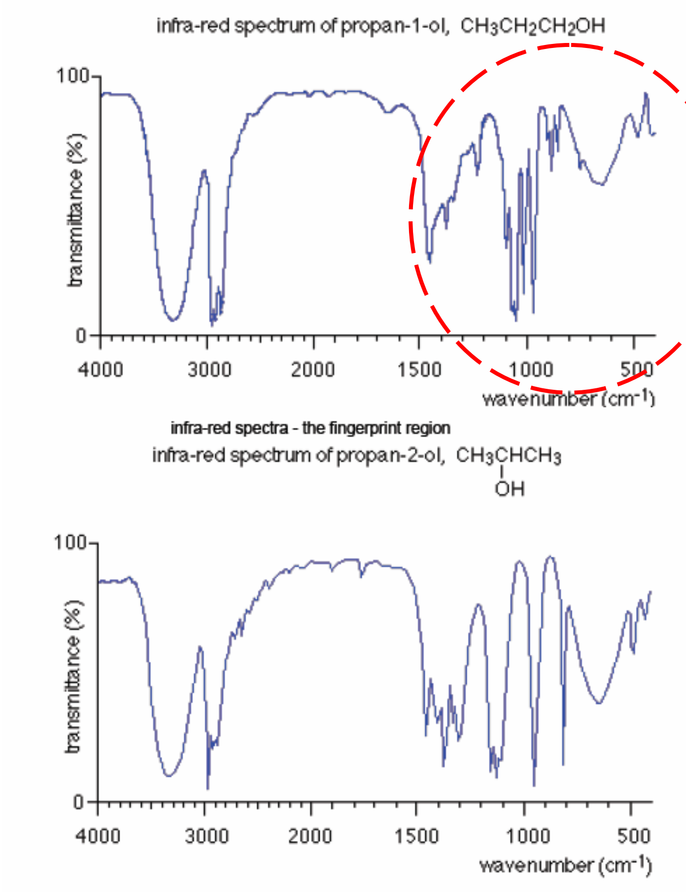
• Parametric sources (Optical Parametric Oscillators, Optical Parametric Amplifiers – OPOs, OPAs), continuum sources

• Few solid-state lasers at specific wavelengths (mainly bulk)

• Quantum-cascaded lasers

# Why MIR?

MIR wavelength interval is called “fingerprint” interval. Any compound has its own absorption spectra.

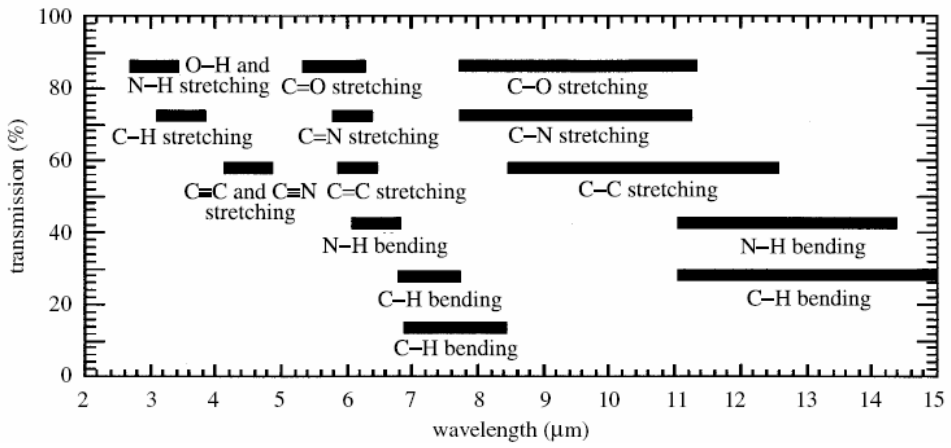


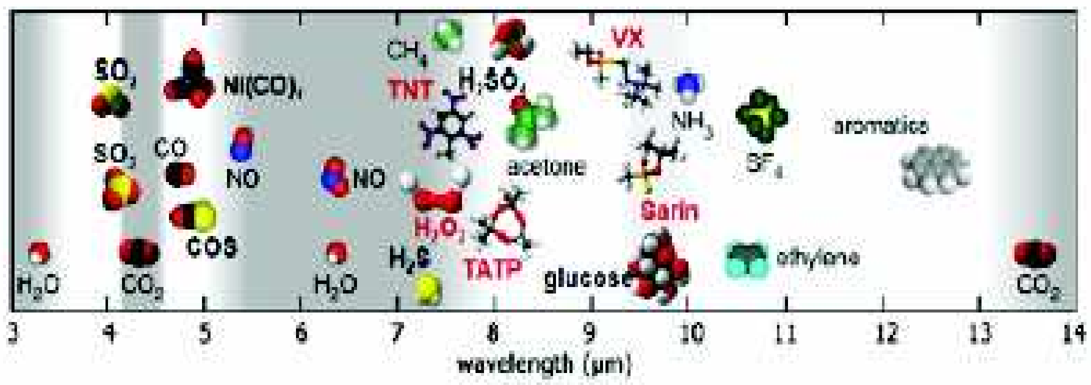

Two isomers

Same atoms, different bounds (different 3D structure)

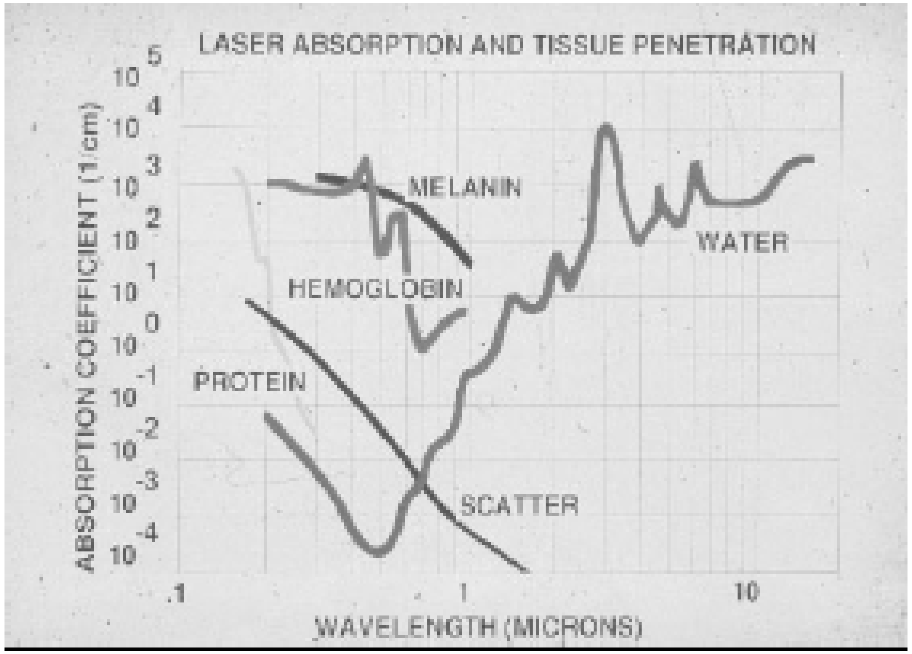
# Why MIR?

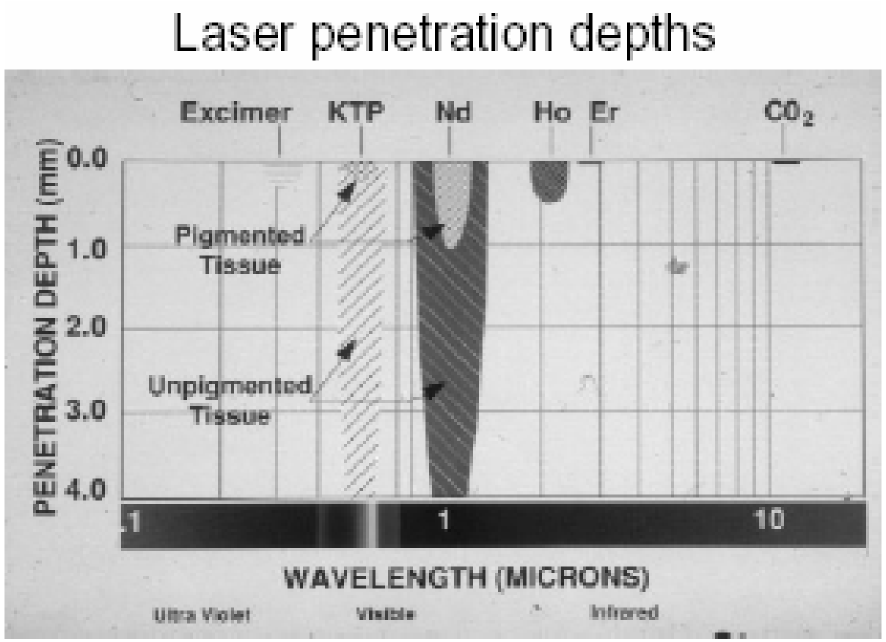
MIR radiation interplay with vibrational levels

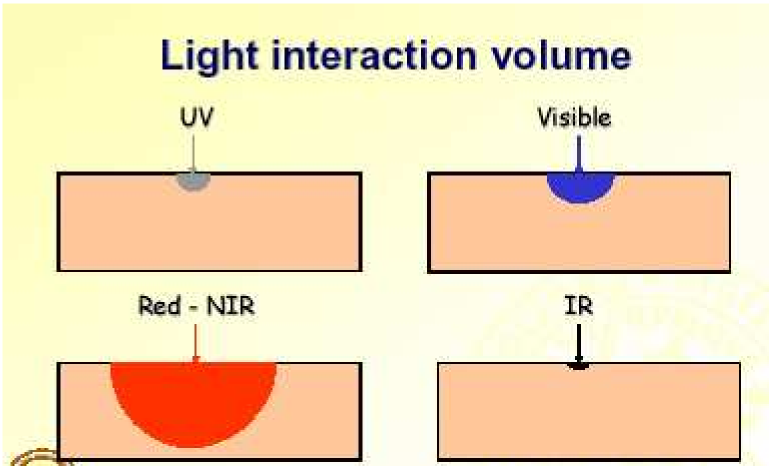


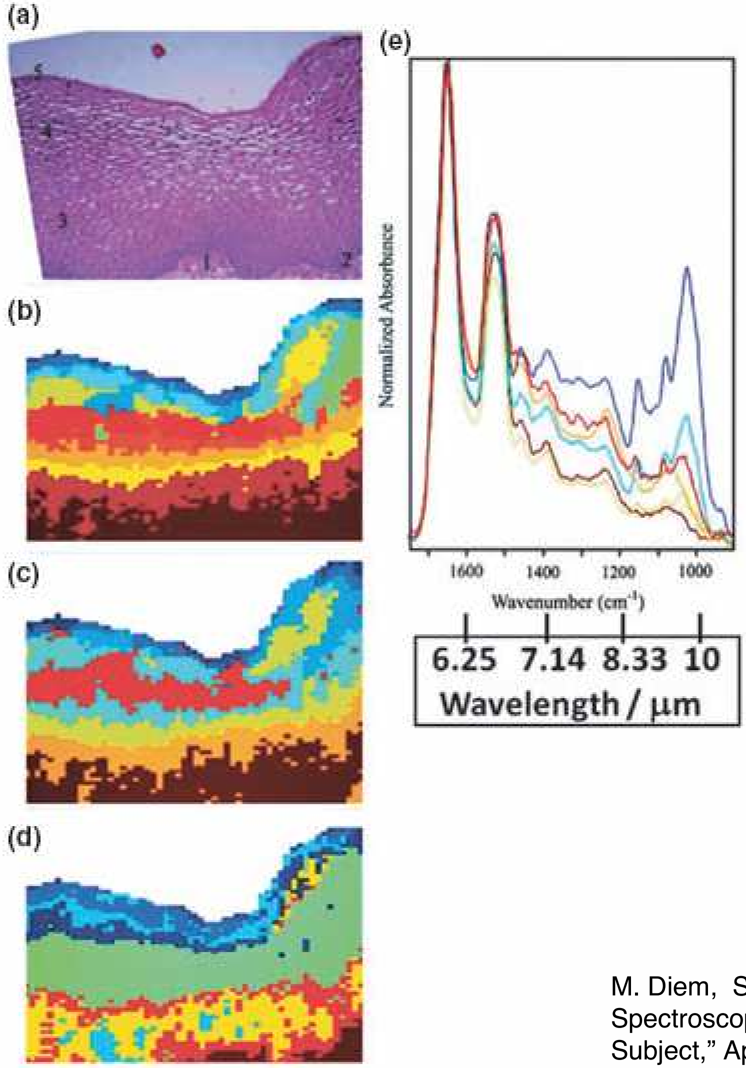
# Absorption: Tissue



# Medical Applications




Recognisation of tissue structure allows *in-vivo* diagnostic of cancer. MIR spectroscopy may recognize cervical cancer.

M. Diem, S. Boydston-White, and L. Chiriboga, “Infrared Spectroscopy of Cells and Tissues: Shining Light Onto a Novel Subject,” Appl. Spectrosc., 53 [4], 148A–161A (1999).

# MIR Sources

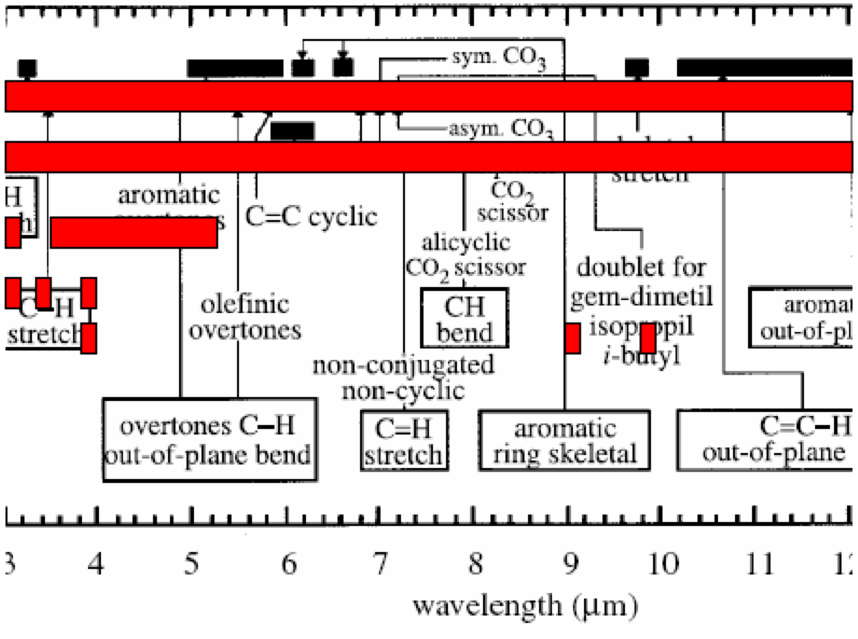
Parametric sources (OPOs, OPAs), SC

QCL

Solid-State Laser (Bulk)

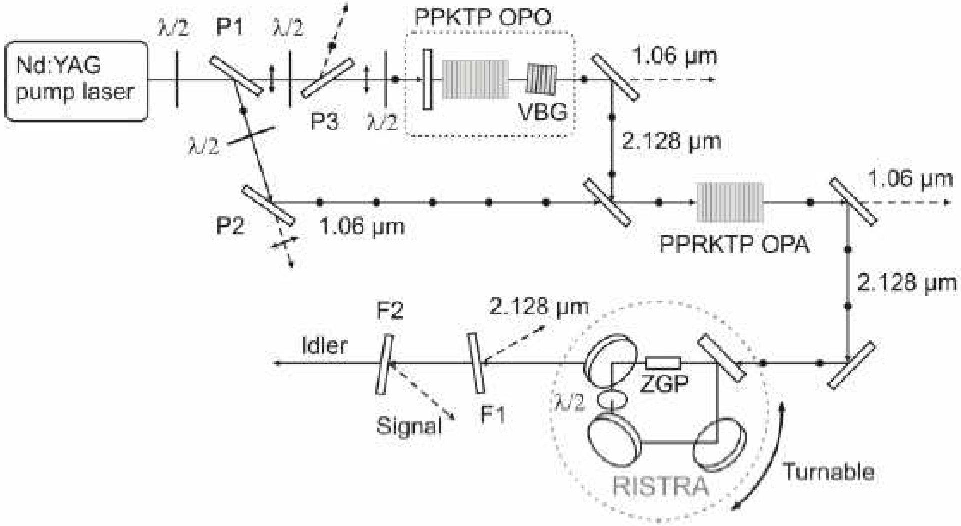
Solid-State Laser (Fiber)

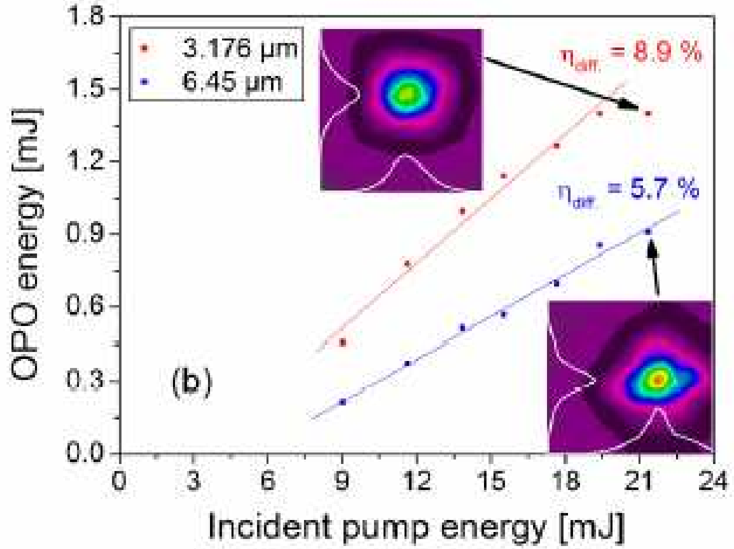
Gas Laser



# Example: 6.5 micron OPO+OPA

# (V. Pasiskevicius, KTH, Sweden)




Submicron surgery for cornea and brain. Efficient ablation in small volume due to high absorption (few ns pulses).

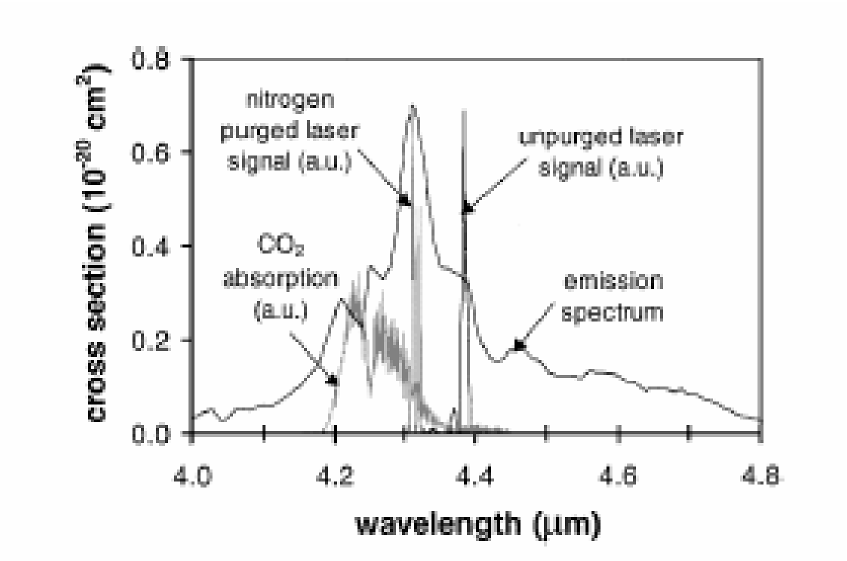
With respect to submicronUV surgery (same small volume/high absorption) MIR thermal energy avoids genetic modification (possibly inducing cancer).

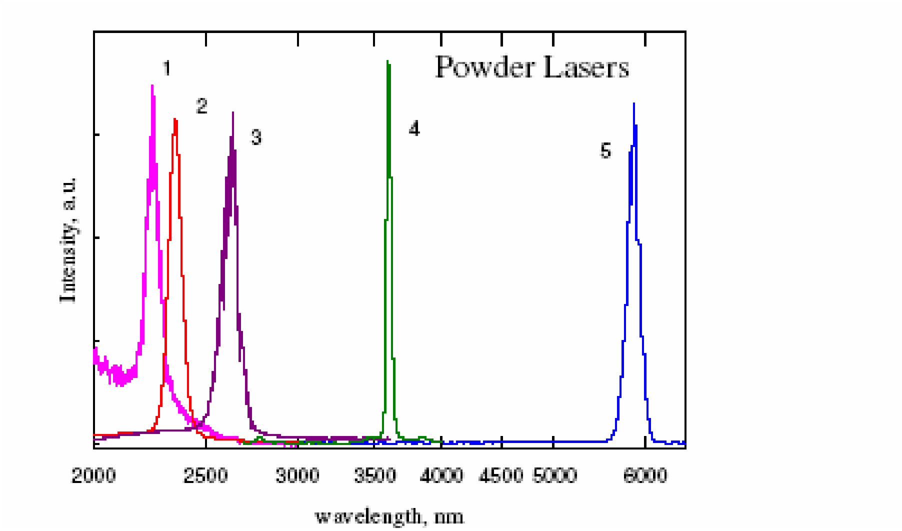
# Solid-State Lasers

A few bulk (crystal) lasers were demonstrated
$Fe^{2+}$-ZnSe: (3.7-5$\mu$m),
Dy-ZnSe: around 4.5 $\mu$m
$Cr^{2+}$-ZnSe at 3.5 $\mu$m

Almost nothing in fiber lasers
Er-doped ZBLAN glass (soft glasses): 3 micron
Other soft glasses doped with Ho (3.5 micron) and Er (4 micron)

# Solid-State Lasers




Dy-doped crystal

N.C.Nostrand et al, Opt. Lett, 24 1215 1999

Random laser: II-VI powders doped with Cr and Fe

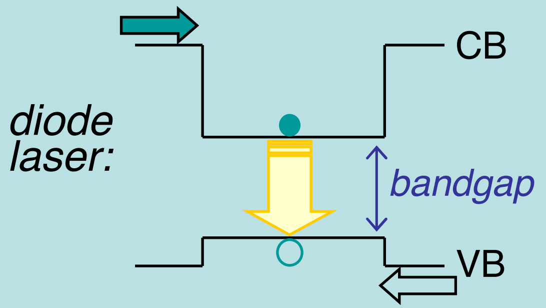
S.B.Mirov et al, Opt.Mat. Express, 1 898 2011

Science 22 April 1994: Vol. 264 no. 5158 pp. 553-556
DOI: 10.1126/science.264.5158.553

## Quantum Cascade Laser

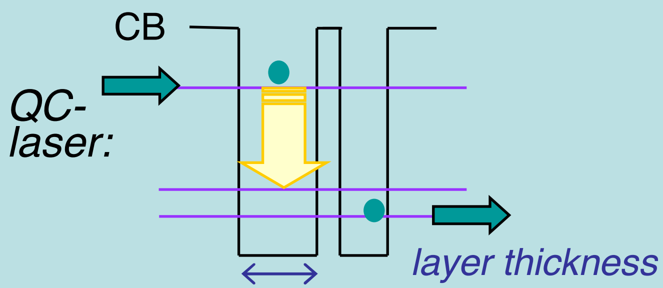
**Jerome Faist, Federico Capasso, Deborah L. Sivco, Carlo Sirtori, Albert L. Hutchinson, Alfred Y. Cho**

# Why is it fundamentally different from diode lasers? (F. Capasso)




**Diode Laser**

- Light from e-h recombination
  *wavelength controlled by bandgap*
- Gain limited by band-structure (absorption coefficient)
- One photon per e-h pair injected above threshold

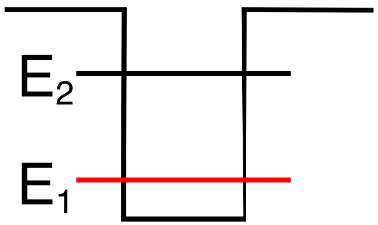



**Quantum Cascade Laser**

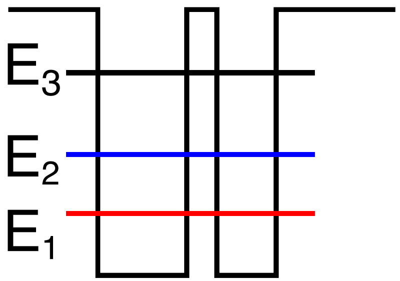
- Light from quantum jumps between subbands
  *Wavelength controlled by thickness:* (4 to 160μm)
- Gain limited by electron density in the excited state:
  i.e. by maximum current one can inject
- N photons per electron injected above threshold
  N is the number of stages

- **Quantum design of all laser properties through design of wavefunctions, matrix elements, relaxation times, transport,…..**

# Basic Building Blocks of Quantum Cascade Lasers

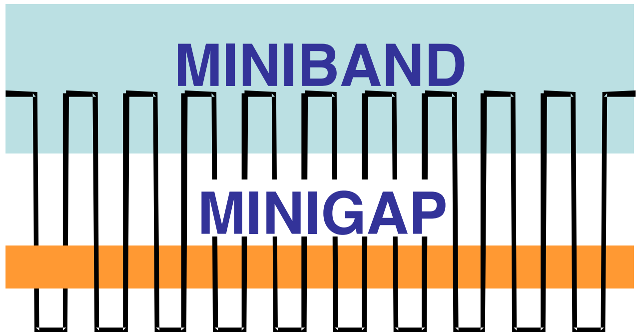



one
quantum-well




coupled
quantum-wells

more flexible design,
all transitions allowed
(asymmetric structures)

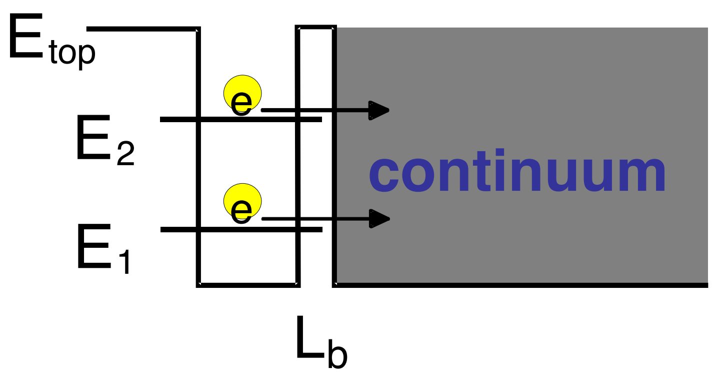



superlattice

recover transport in
growth direction,
Bragg reflection

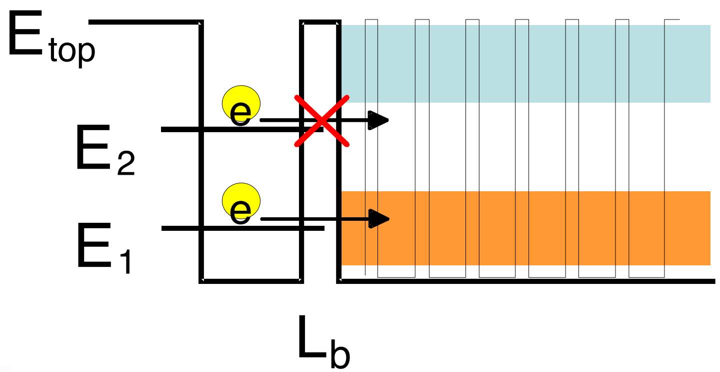
**Source: F. Capasso**

# Electron lifetime and escape into continuum: suppression of excited lifetime




**Escape into continuum**

$\boxed{\tau_2 < \tau_1}$



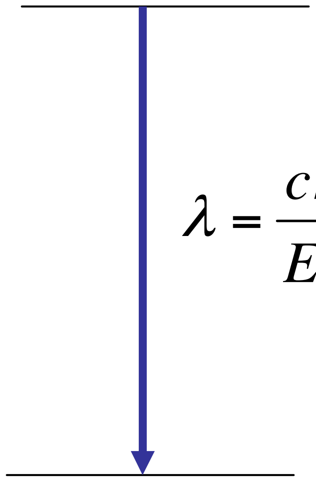

$\boxed{\tau_2 >> \tau_1}$

**Escape into superlattice: electrons can't tunnel into minigap:**

**Source: F. Capasso**

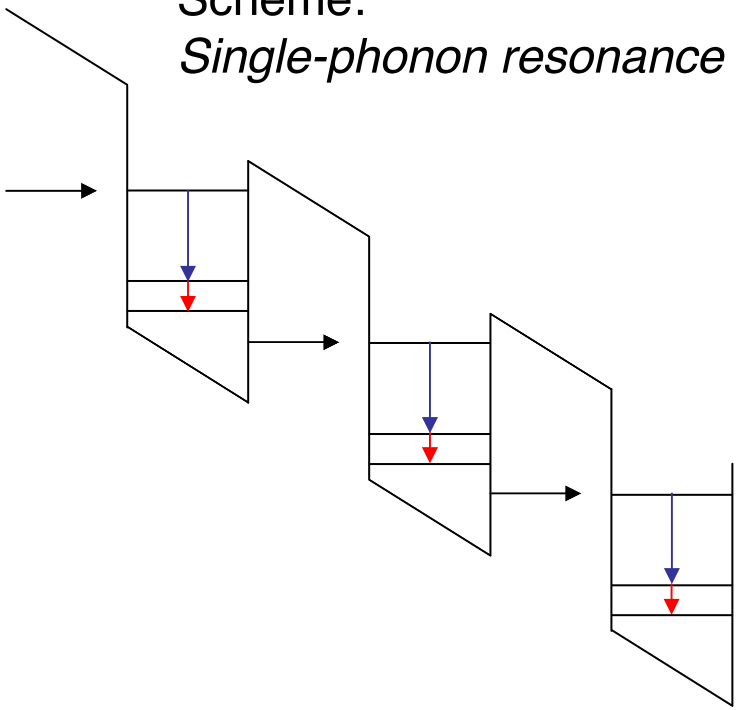
# Quantum cascaded lasers

Semiconductor
transition



$$\lambda = \frac{ch}{E_g}$$

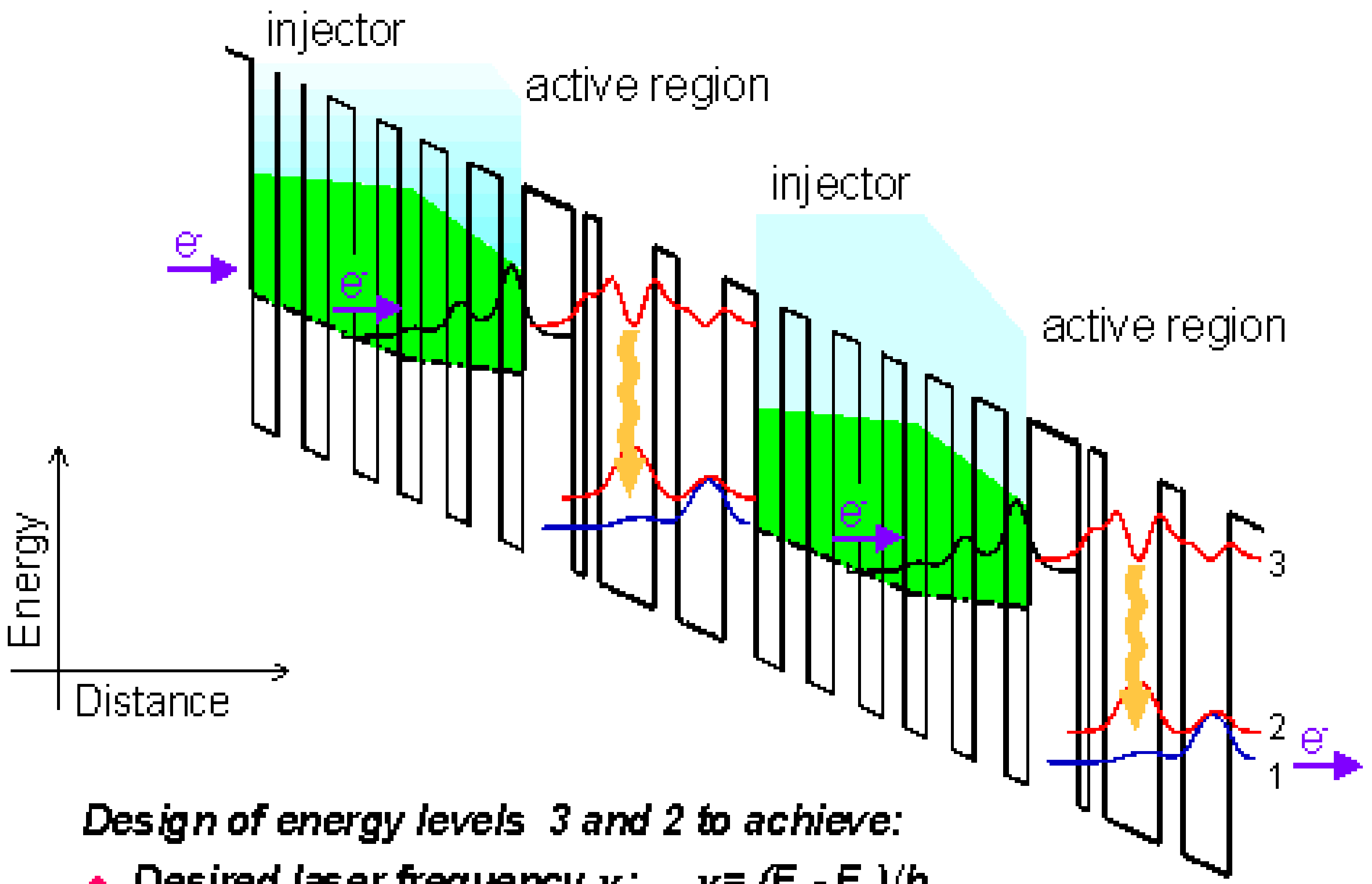
Multi-quantum well laser:
intersubband transition
Scheme:
*Single-phonon resonance design*



Repeating the process over tens or even hundred's of quantum wells (a cascade), a higher optical gain and several photons for a single injected electron are obtained. The main first drawback is high electrical voltage and liquid nitrogen temperature cooling.

# *Quantum design of QC-laser*

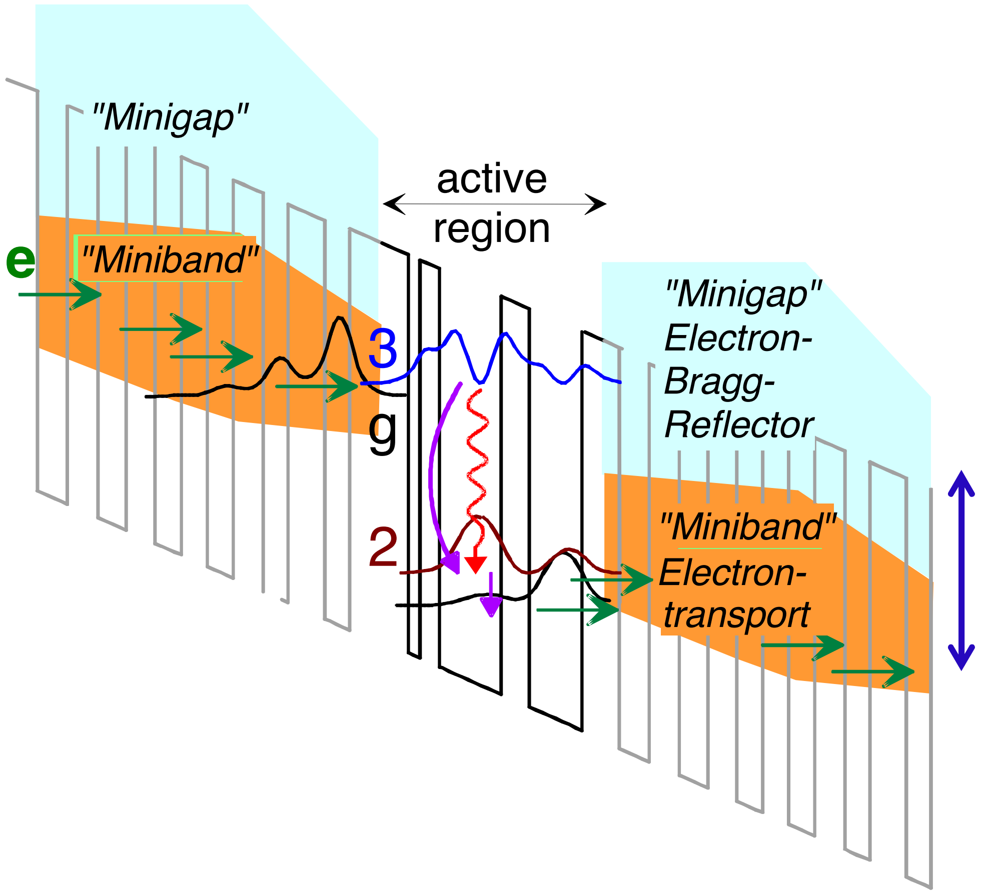
*J. Faist, F. Capasso, C. Sirtori, D. L. Sivco, J. N. Baillargeon, A. L. Hutchinson, S. N. G. Chu, and A. Y. Cho, Appl. Phys. Lett.* ***68****, pp. 3680-3682 (1996).*

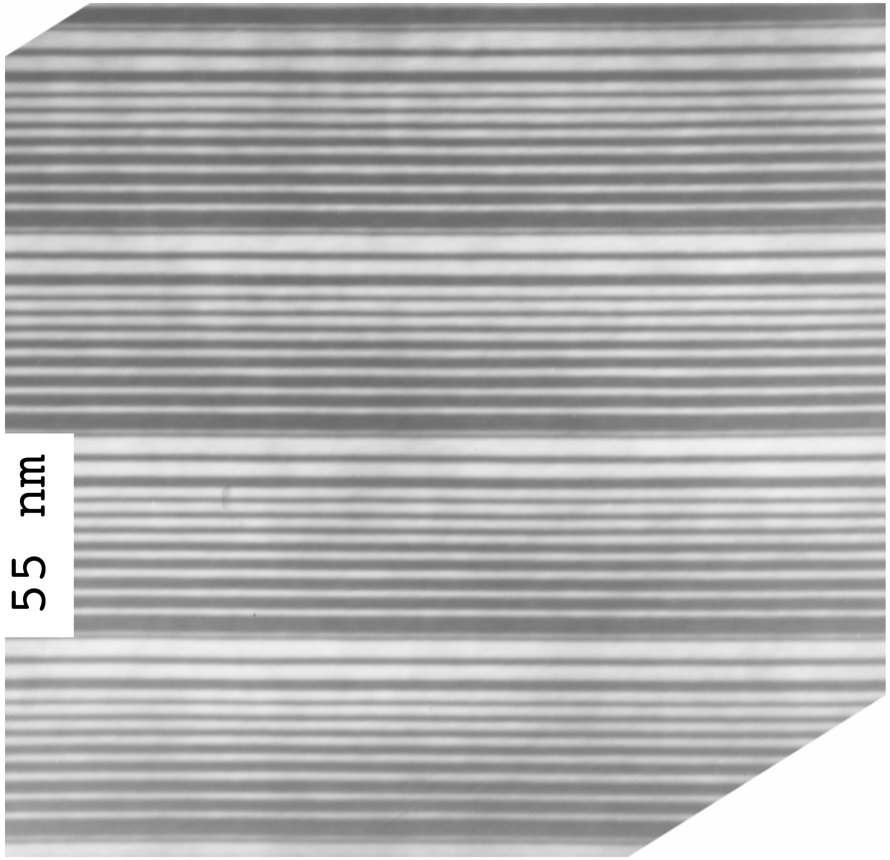



***Design of energy levels 3 and 2 to achieve:***

- ***Desired laser frequency ν:*** $\nu = (E_3 - E_2)/h$
- ***Light amplification: level 3 full of electrons; level 2 empty of electrons***

# Band structure Engineering



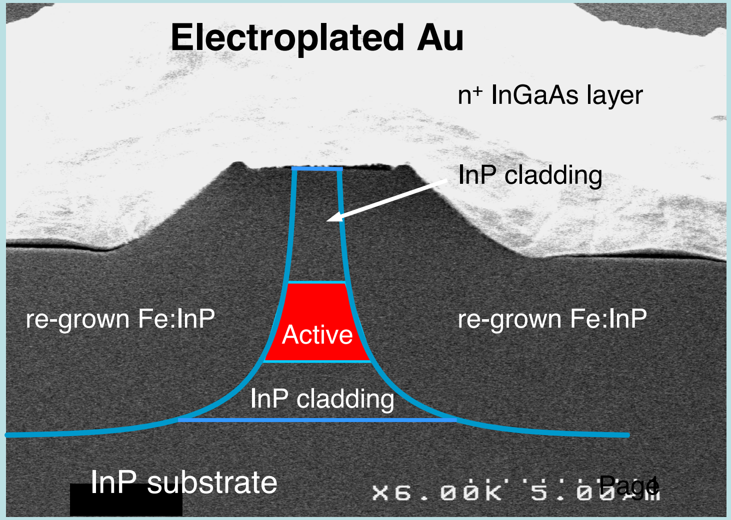

AlInAs/GaInAs grown by Molecular Beam Epitaxy (MBE)

**Electron lifetime engineering**

**Design of population inversion: $\tau_{32} >> \tau_2$**

**Bragg reflectors to suppress electron escape**

# Buried heterostructures




$$\frac{dF}{dt} = \left[ N_p \Gamma_p v_g g_c (n_2 - n_1) - \frac{1}{\tau_p} \right] F + N_p \beta \frac{n_2}{\tau_{sp}}$$

$$\frac{dn_2}{dt} = \frac{n_{SL}}{\tau_{SL}} - \frac{n_2}{\tau_2} - \Gamma_p v_g g_c (n_2 - n_1) F$$

$$\frac{dn_1}{dt} = \frac{n_2}{\tau_2} - \frac{n_1}{\tau_1} + \Gamma_p v_g g_c (n_2 - n_1) F$$

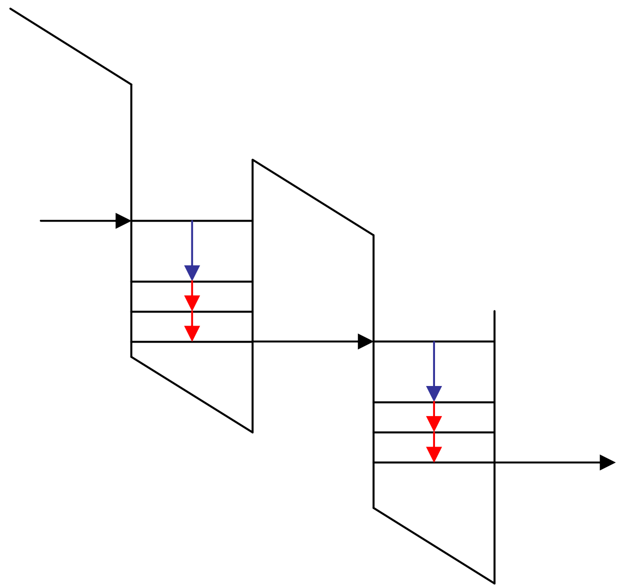
$$\frac{dn_{SL}}{dt} = \frac{n_1}{\tau_1} - \frac{n_{SL}}{\tau_{SL}}$$

InP cladding

# Quantum cascaded lasers

- lasers based on AlInAs/GaInAs and GaAs/AlGaAs material systems are developed.
- Both structures consist of a periodic repetition of two regions, an as injector and a coupled quantum well active region.

# Quantum cascaded lasers: two-phonon resonance design



compared to the single-phonon resonance design (1994) the two phonon resonance design has the advantage of lowering carrier population in the lower laser level 3 due to reduced carrier *thermal* filling into this state from the lowest active region state 1. Energy of the resonance define the layer thickness.

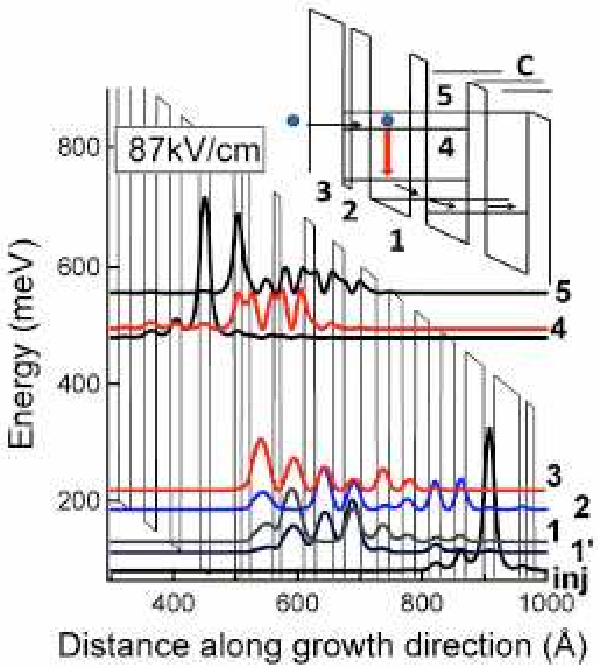
Energy of non-radiative transitions matches the a particular energy value (longitudinal phonon energy) to decrease the lifetime and effectively deplete the lower laser level.

# Quantum cascaded lasers: non-resonant scheme

APPLIED PHYSICS LETTERS 95, 141113 (2009)

**3 W continuous-wave room temperature single-facet emission from quantum cascade lasers based on nonresonant extraction design approach**

A. Lyakh,[1] R. Maulini,[1] A. Tsekoun,[1] R. Go,[1] C. Pflügl,[2] L. Diehl,[2] Q. J. Wang,[2] Federico Capasso,[2] and C. Kumar N. Patel[1,3,a)]



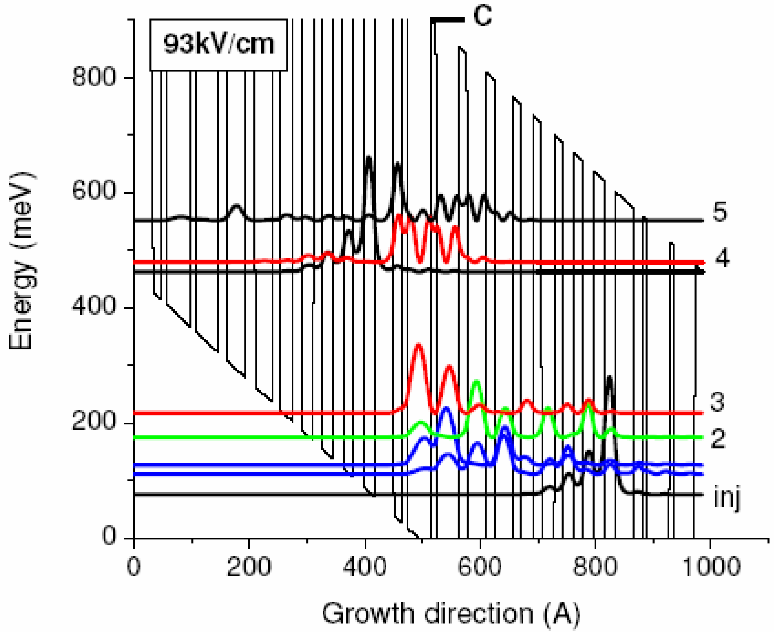

You can increase the energy between level 2 and 1 if you allow two final states 1 and 1'. The $\tau_2$ carrier lifetime is comparable.

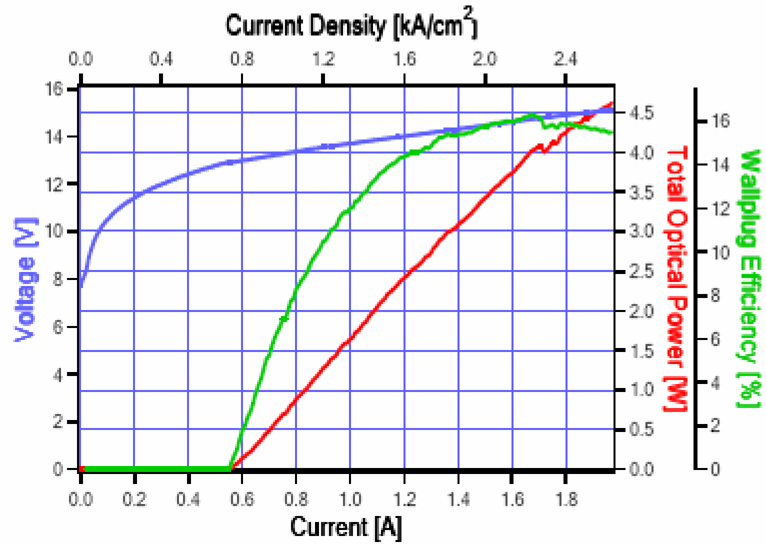
# Quantum cascaded lasers: non-resonant scheme

13 February 2012 / Vol. 20, No. 4 / OPTICS EXPRESS 4382

**Tapered 4.7 μm quantum cascade lasers with highly strained active region composition delivering over 4.5 watts of continuous wave optical power**

Arkadiy Lyakh,[1] Richard Maulini,[1] Alexei Tsekoun,[1] Rowel Go,[1] and C. Kumar N. Patel[1,2,*]




Increase of barrier height increases injection efficiency (lower probability to escape to continuum)

$$\gamma_{43} = E_c^{\,2}\, \Delta^2\, \Lambda^2 \sum_k \left[\Psi_4^{\,2}(z_k) - \Psi_3^{\,2}(z_k)\right]$$ [*]

[*]A. Wittmann, et al. Appl. Phys. Lett. 93(14), 141103 (2008).

# QCL: state of the art: uncooled laser (RT)

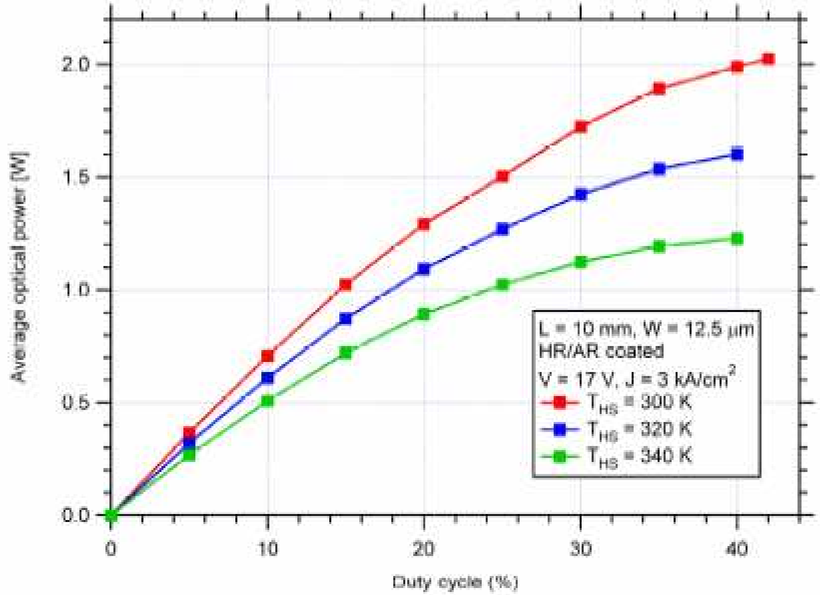



**Figure 10. High temperature performance of uncooled QCW/RT operating QCL at ~4.6 μm**

C. Kumar and N. Patel "High Power Infrared QCLs: Advances and Applications" SPIE Photonic West 2012 Vol. 8268 826802

# QCL: state of the art: uncooled laser (RT)

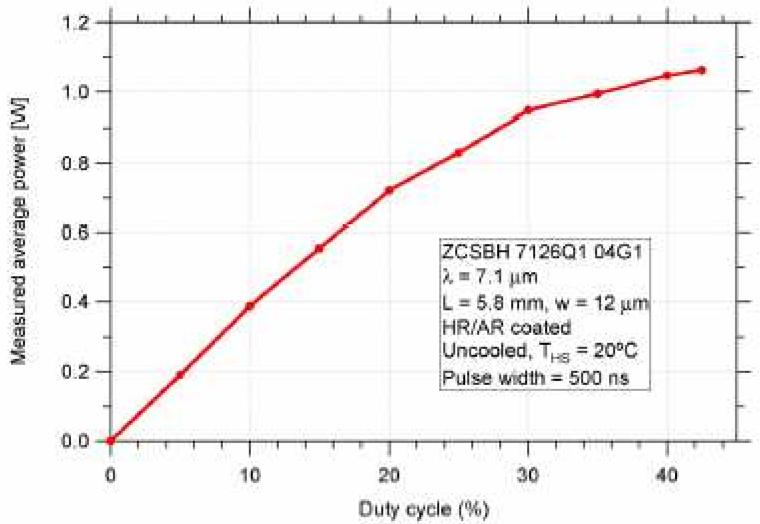



**Figure 13. QCW/RT performance of a ~7.2 µm fully packaged QCL showing average power output at as function of duty cycle**

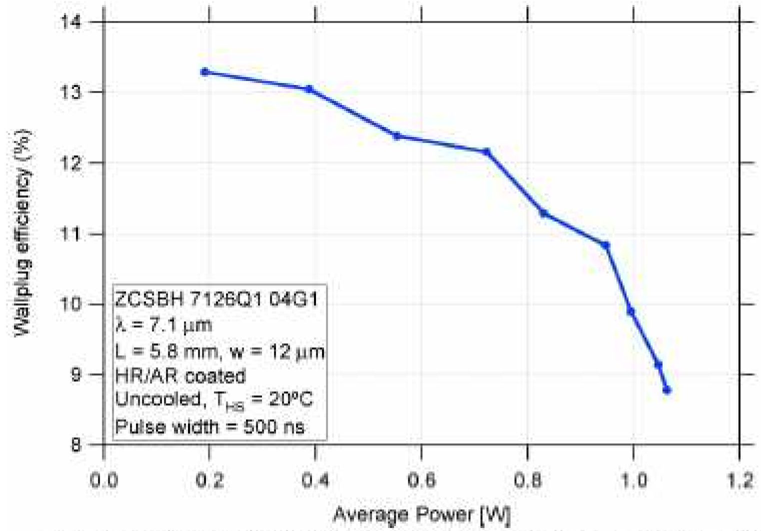



**Figure 14. QCW/RT performance of a ~7.2 µm fully packaged QCL showing system efficiency as function of power output**

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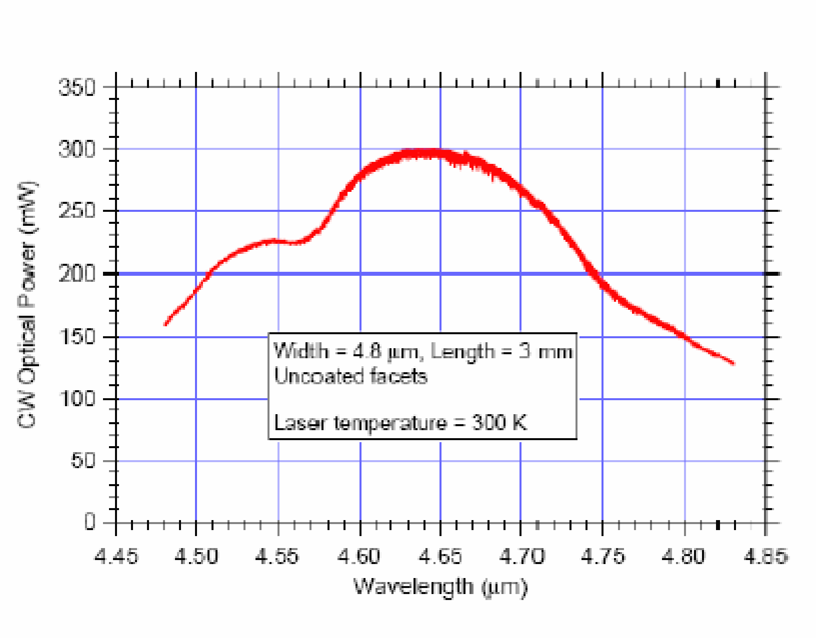
# QCL: Tunable

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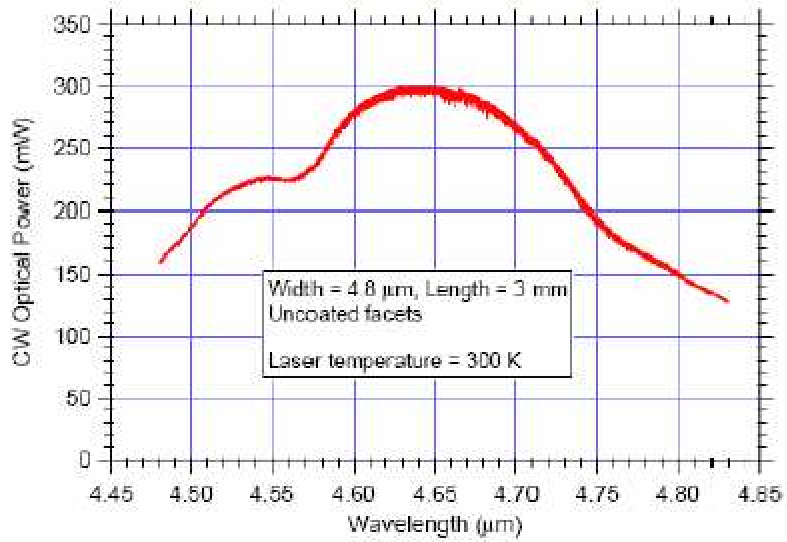
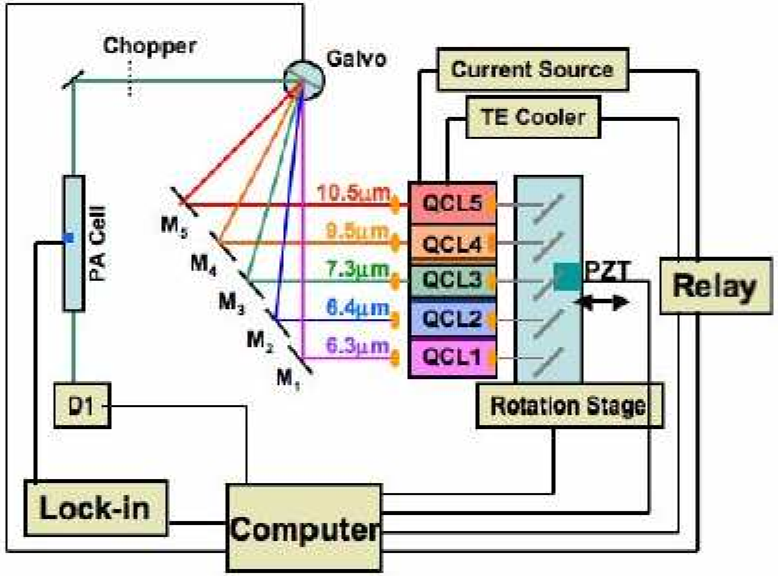
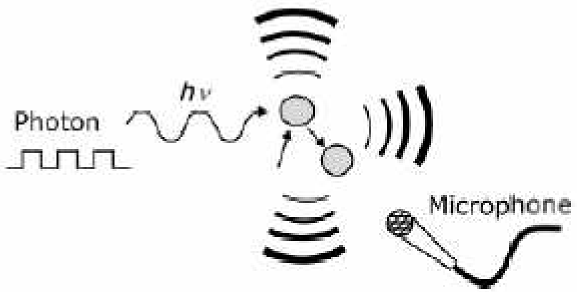
# QCL: Detection of Gas Traces



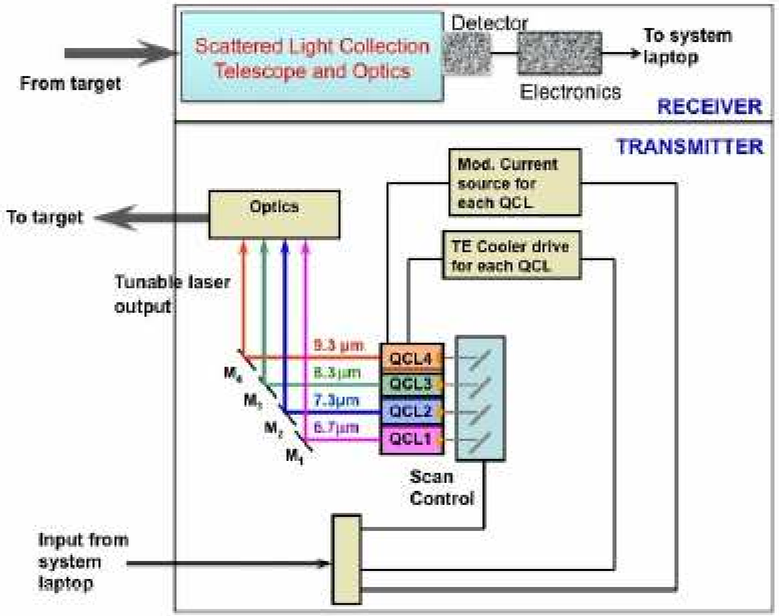




In contrast with other mid-IR absorption techniques, PAS is an indirect technique in which the effect on the absorbing medium and not direct light absorption is detected. Light, from either pulsed or chopped CW laser sources produces a transient temperature rise in an absorbing medium via non-radiative relaxation processes, which then translates into a pressure change or sound wave as illustrated in Fig. 9. This is detected with a sensitive microphone(s). The acoustic signal is directly related to the concentration of the absorbing molecules in the cell. For CW laser sources, there are two modes of operation for PAS, either the exciting light can be modulated at a frequency away from any cell resonance or it can be adjusted to coincide with an acoustic resonant frequency. The

C. Kumar and N. Patel "High Power Infrared QCLs: Advances and Applications" SPIE Photonic West 2012 Vol. 8268 826802

# QCL: stand-off detection of explosives

# Conclusions

MIR is a promising region for laser sources

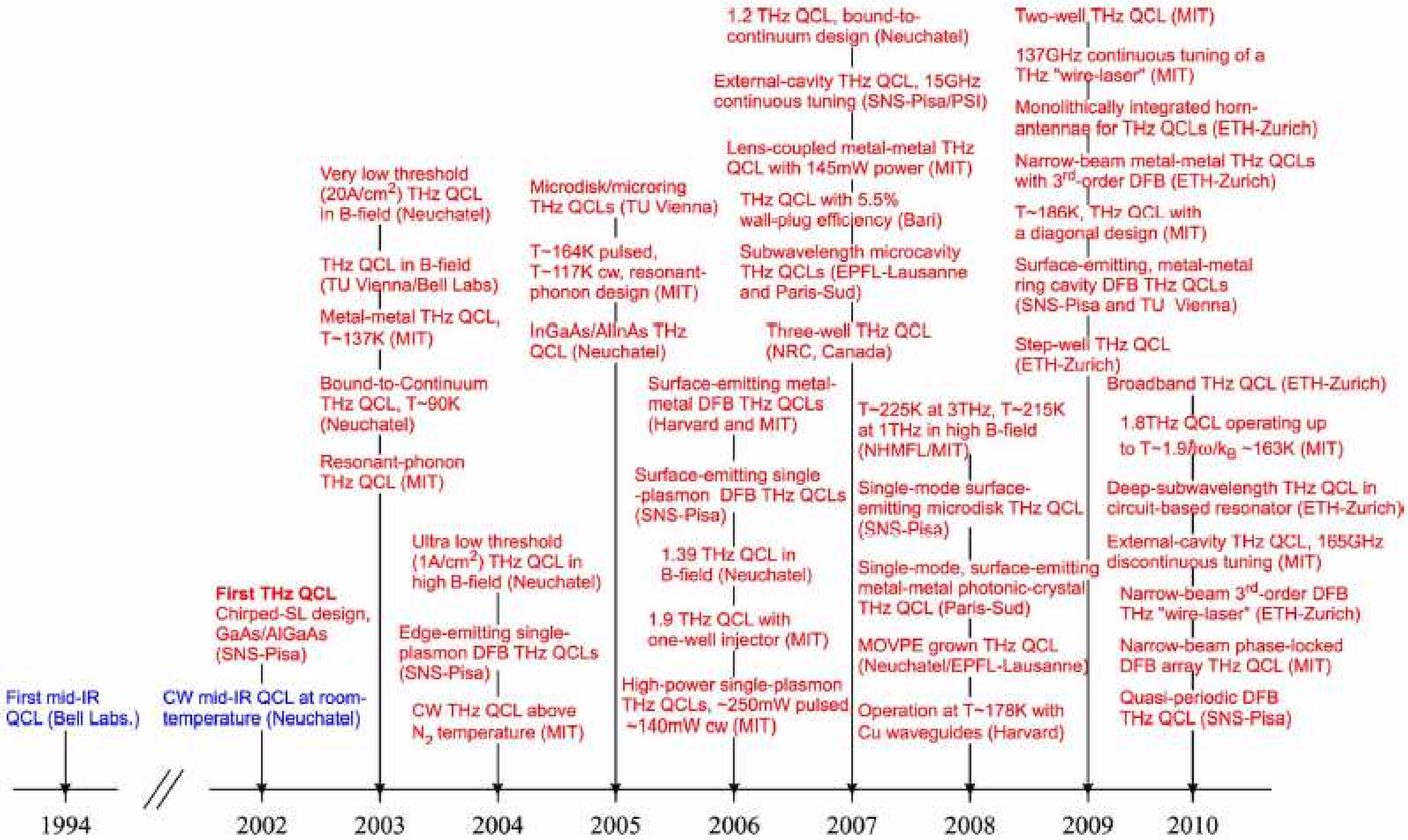
QCL are very versatile (cover full MIR spectrum until 10 micron) but luck of reliability at RT and CW power is limited

Solid-state lasers are still to be developed

OPOs/OPAs are too complex to impact everyday life

**A LOT OF WORK TO BE DONE!**

# THz QCL




Sushil Kumar, “Recent Progress in Terahertz Quantum Cascade Lasers” IEEE J. Sel. Topics in Quant. Electron. 17 (1), p. 38 (2011)