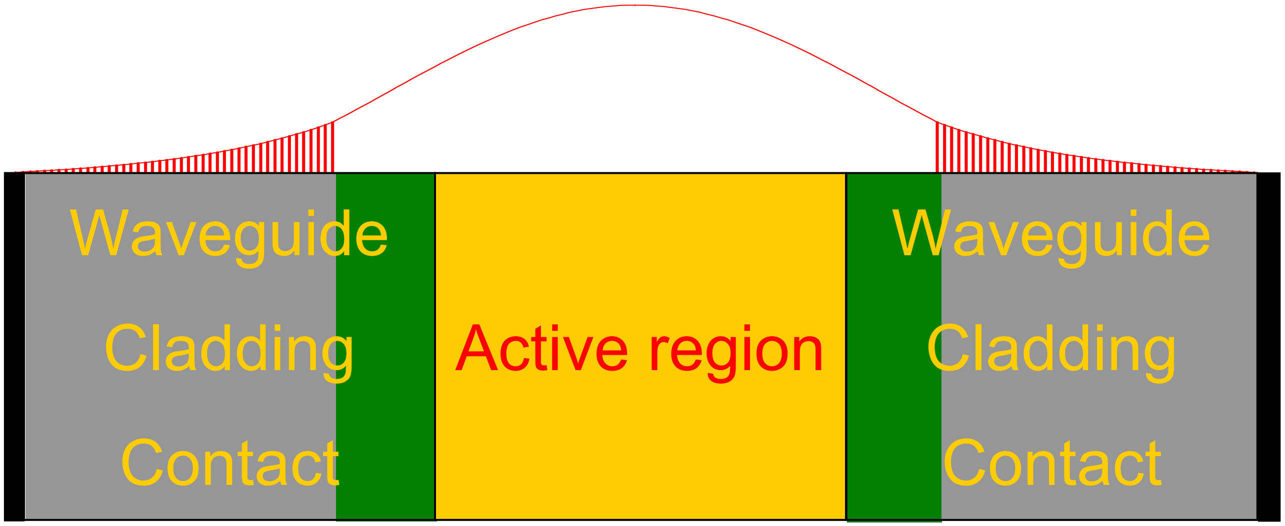
Semiconductor laser design goals



To provide excellent injection properties with minimum optical loss **α** and heating

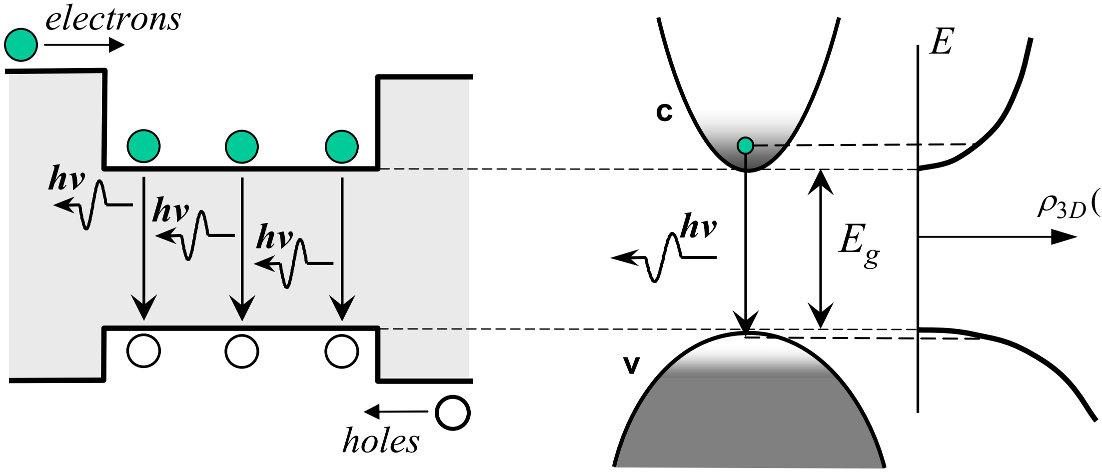
To achieve maximum material gain **G** at given **I**

To optimize optical confinement **Γ**

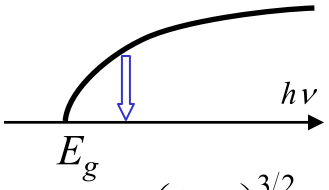
$$\boxed{g = \Gamma \cdot G - (\alpha_i + \alpha_m)}$$

Semiconductor Lasers: 2D vs. 3D confinement

double-heterostructure laser



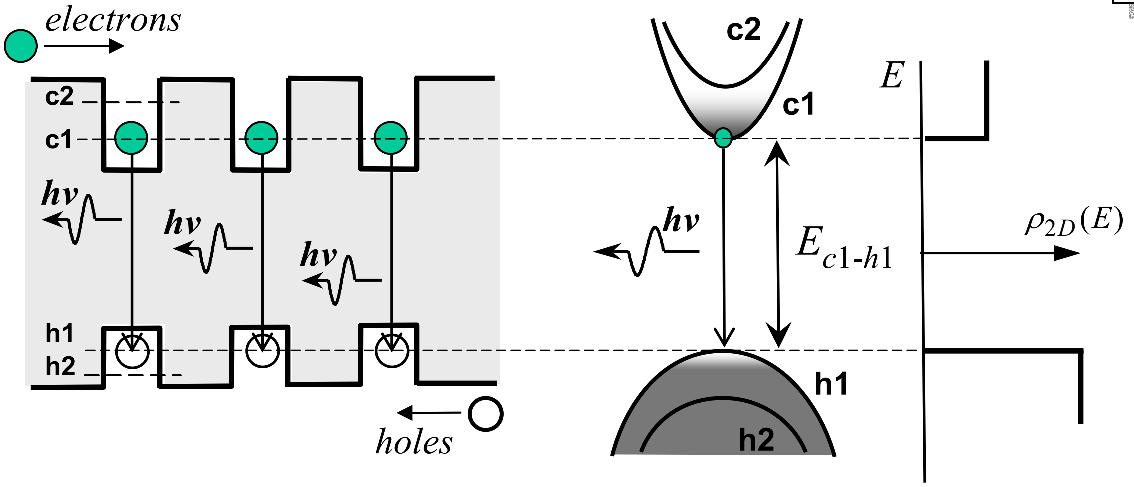
3D joint DOS



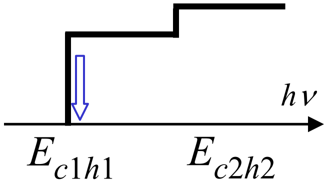
$$\rho(h\nu) = \frac{1}{2\pi^2}\left(\frac{2m_r}{\hbar^2}\right)^{3/2}\sqrt{h\nu - E_g}$$

$$\boxed{m_r^{-1} = m_c^{-1} - m_v^{-1} = m_c^{-1} + m_h^{-1}}$$

quantum well (QW) laser



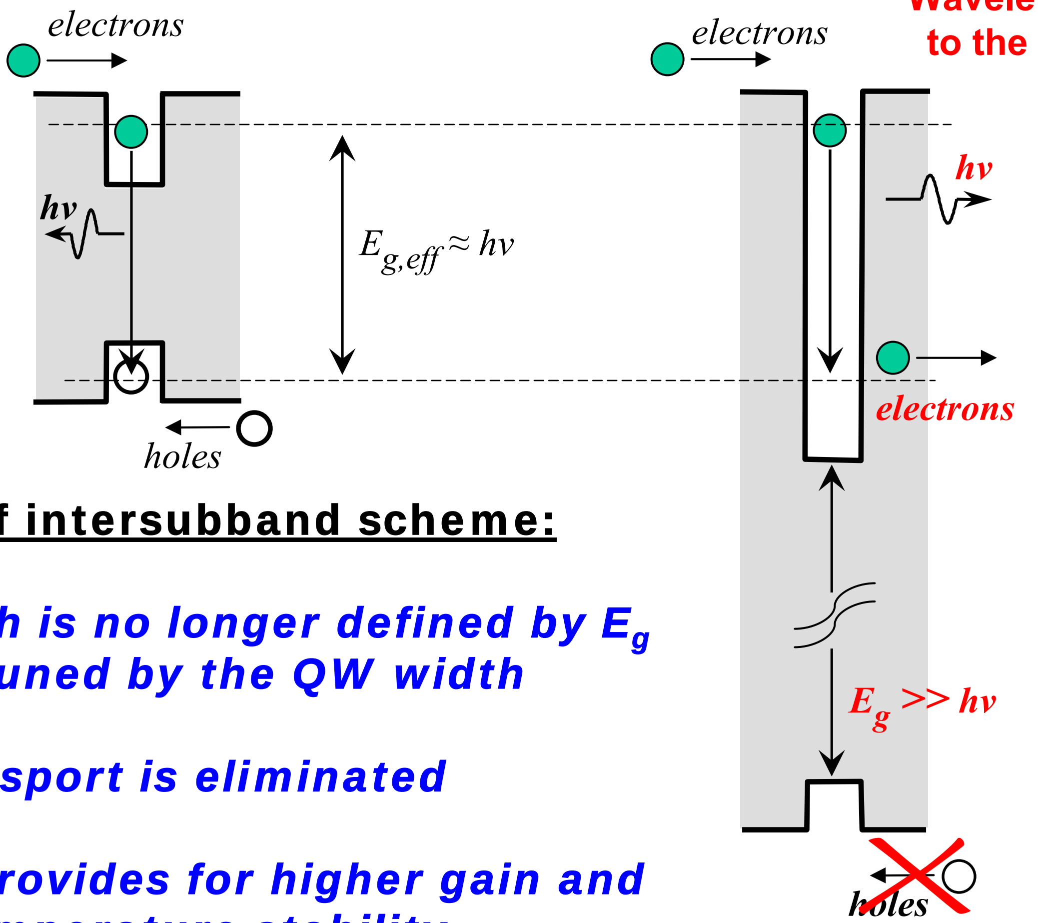
2D joint DOS



$$\rho(h\nu) = \frac{m_r}{\pi\hbar^2}$$

Interband and Intersubband lasing

Wavelength is restricted
by
material bandgap



Wavelength is uncoupled
to the material bandgap

Advantages of intersubband scheme:

Lasing wavelength is no longer defined by E_g and can be tuned by the QW width

Hole transport is eliminated

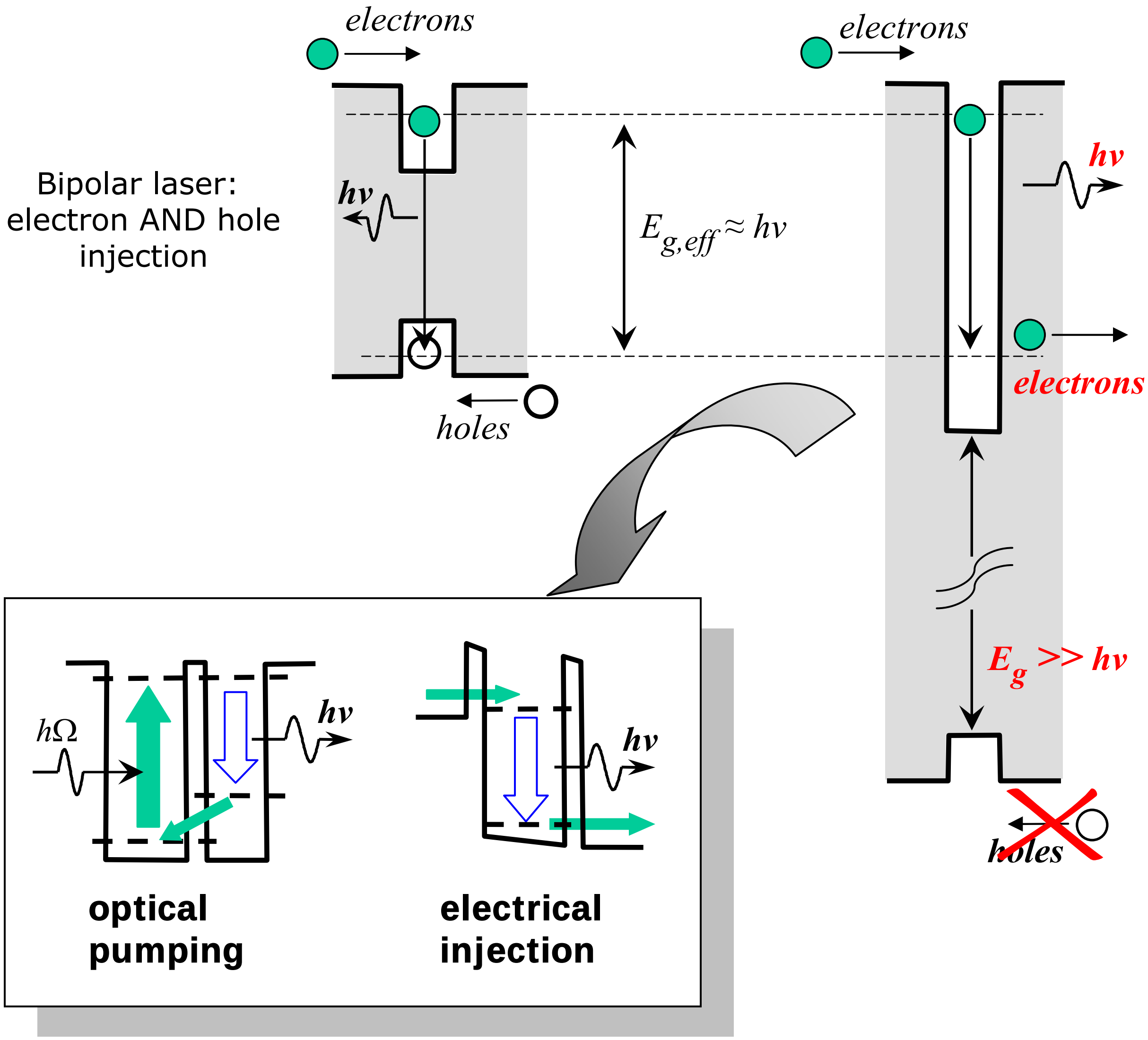
δ-like joint DOS provides for higher gain and better temperature stability

Monopolar transport offers electron recycling

Interband and Intersubband Lasing

interband lasing scheme

intersubband lasing scheme



Bipolar laser:
electron AND hole
injection

Advantages:

lasing wavelength can be tuned by the QW width

δ-like joint DOS provides for higher gain and better temperature stability

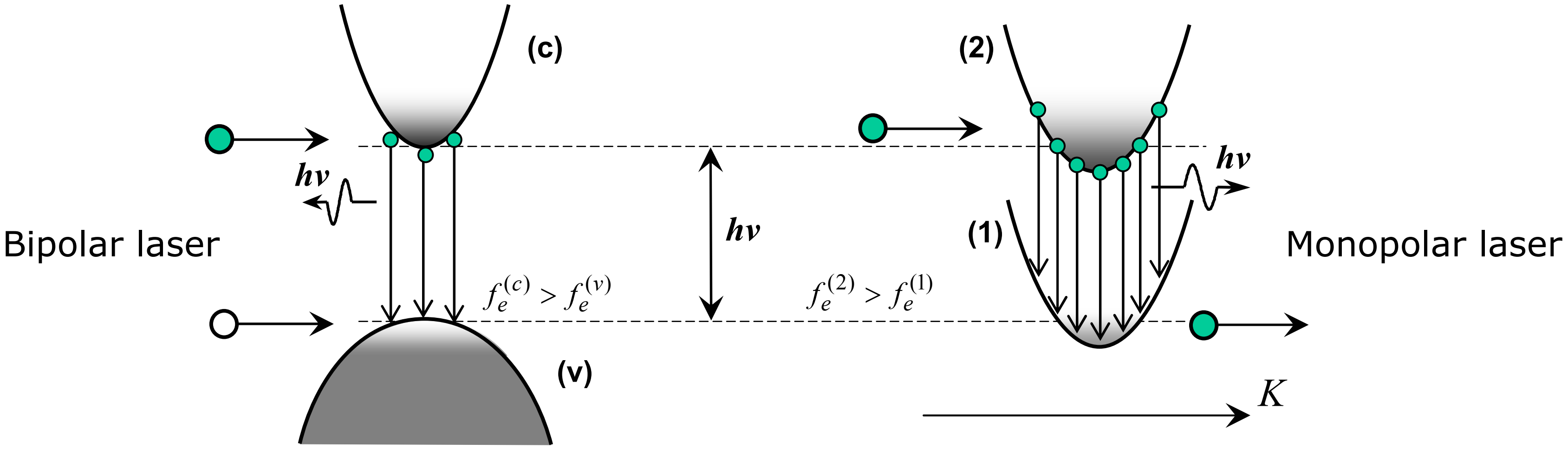
monopolar transport offers electron recycling

fast electron relaxation allows HF modulation

lasing wavelength is no longer defined by E_g

hole transport is eliminated

δ-like joint DOS provides for higher gain



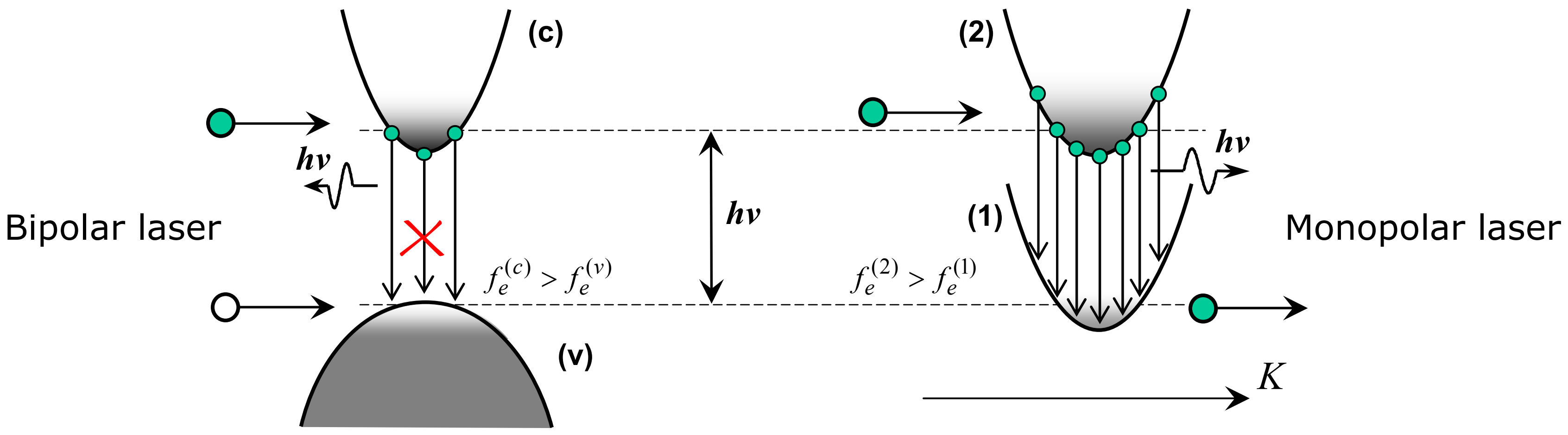
$$G(h\nu) \propto \rho(h\nu)\left[f_2(K) - f_1(K)\right]$$

- ***In intersubband lasers δ-like joint density of states provides for higher optical gain***

- ***Transparency current is negligible in intersubband lasers due to small electron population in the lower lasing states***

Optical Gain

interband lasing **intersubband lasing**



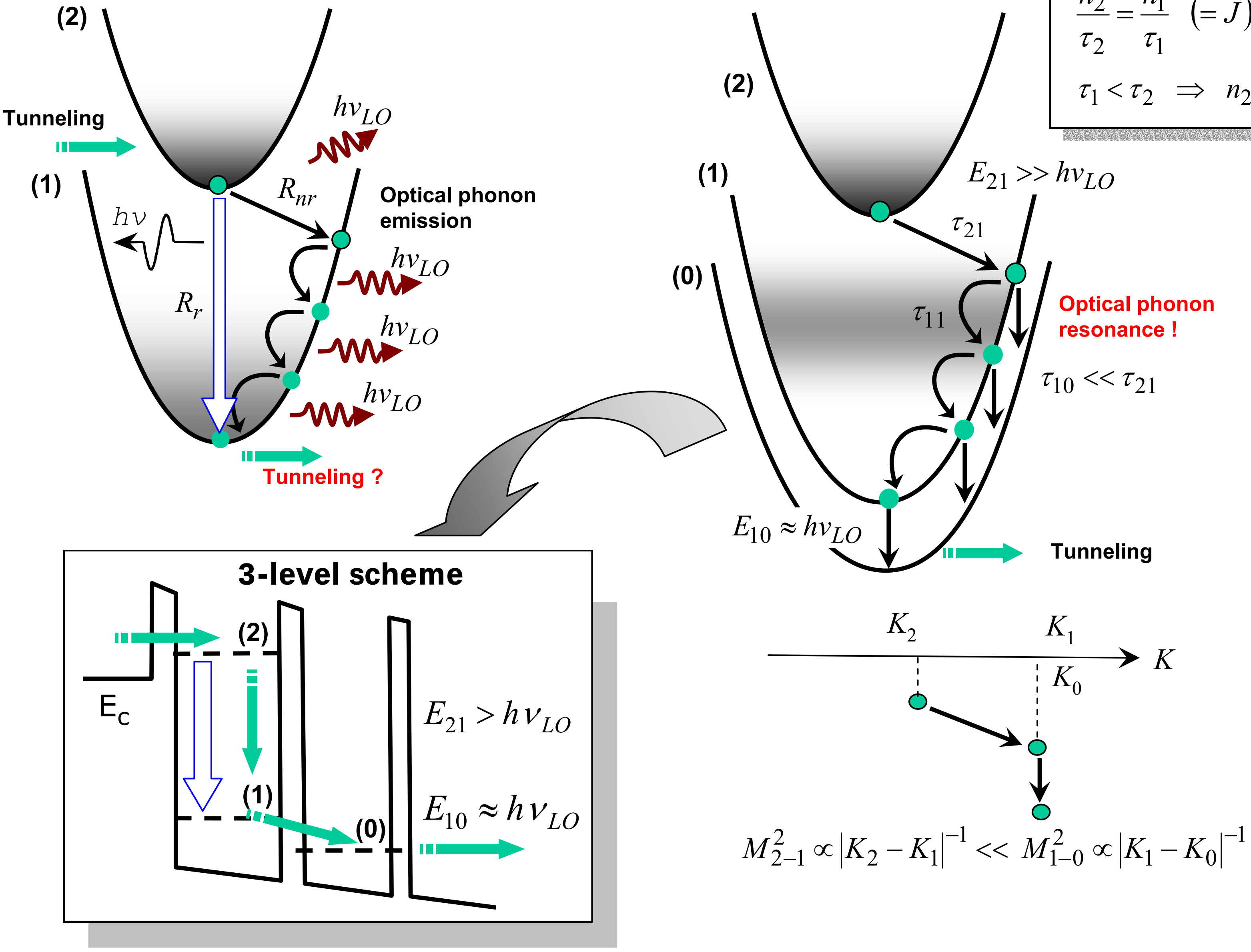
$$\boxed{G(h\nu) \propto \rho(h\nu)\left[f_2(K) - f_1(K)\right]}$$

$$\rho(E) = \frac{\rho(K)}{\left|V_2(K) - V_1(K)\right|} \longrightarrow \rho_{2D}(E) = \frac{K}{\pi}\left|\frac{dE_2(K)}{dK} - \frac{dE_1(K)}{dK}\right|^{-1} = \frac{1}{\pi\hbar^2}\left|\frac{1}{m_2} - \frac{1}{m_1}\right|^{-1} = \frac{m_r}{\pi\hbar^2}$$

Intersubband Kinetics

$$\frac{n_2}{\tau_2} = \frac{n_1}{\tau_1} \quad (= J)$$

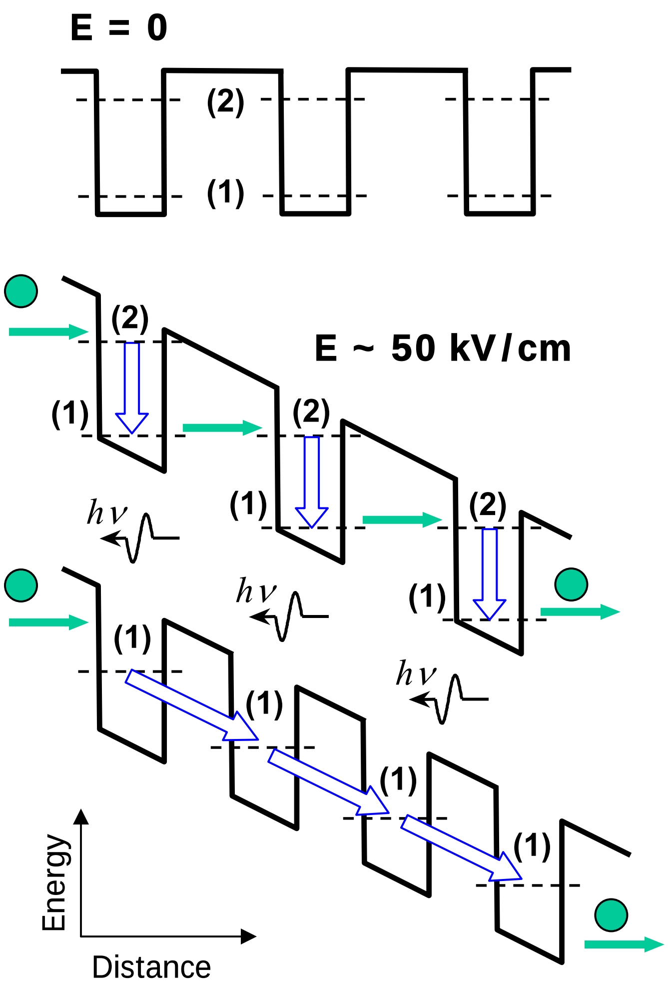
$$\tau_1 < \tau_2 \quad \Rightarrow \quad n_2 > n_1$$



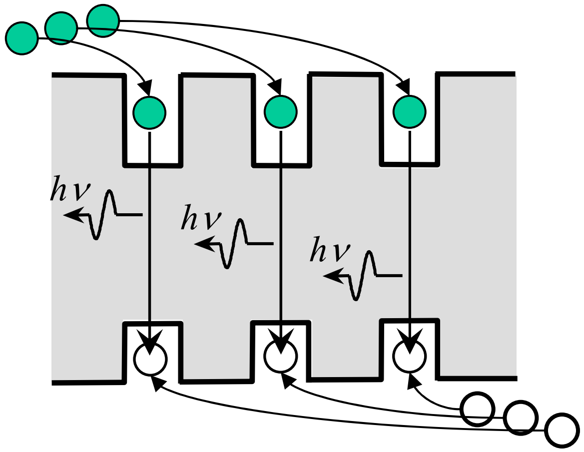
$$M_{2-1}^2 \propto |K_2 - K_1|^{-1} << M_{1-0}^2 \propto |K_1 - K_0|^{-1}$$

Quantum Cascade Laser

quantum cascade laser



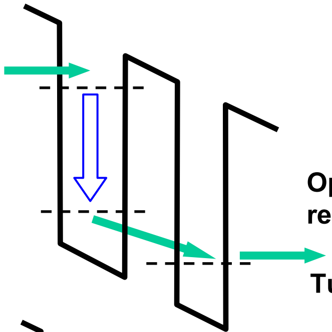
quantum well laser



Advantages of the cascaded scheme:

- quantum efficiency in excess of 1 allows high-power RT operation;
- electric field tunability due to Stark effect;
- multy-wavelength operation;
- electrically uniform active region;
- large confinement factor.

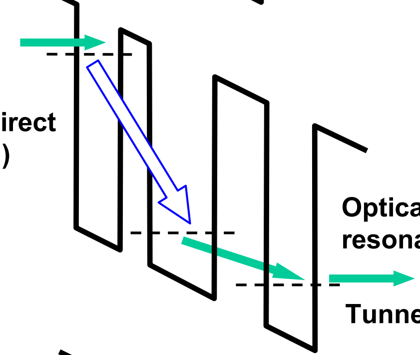
Laser design elements: Active Region



2QW, direct (intrawell)

Optical phonon resonance

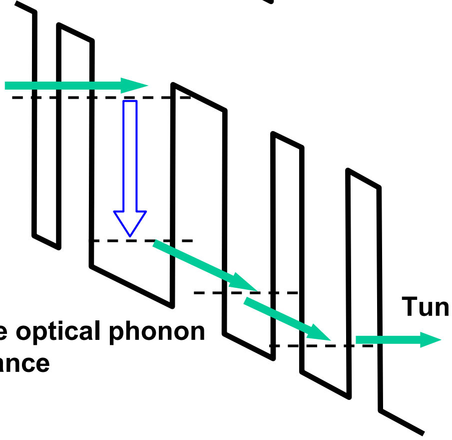
Tunneling



3QW, indirect (interwell)

Optical phonon resonance

Tunneling

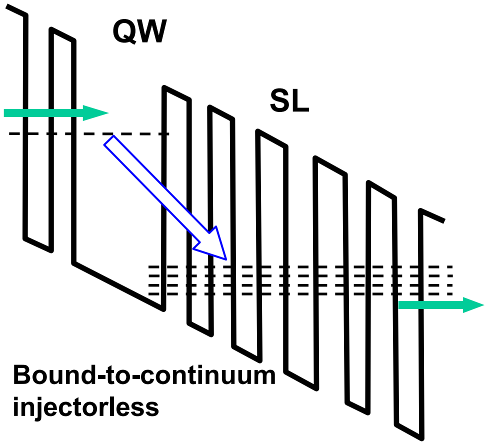


Tunneling

4QW, direct transition

Double optical phonon resonance

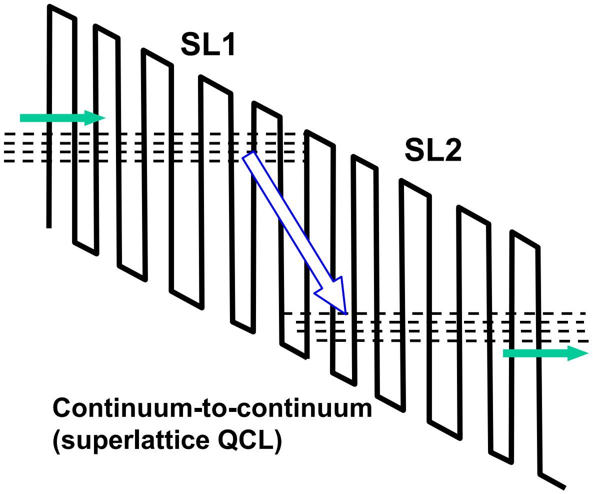
Tunneling



QW

SL

Bound-to-continuum injectorless

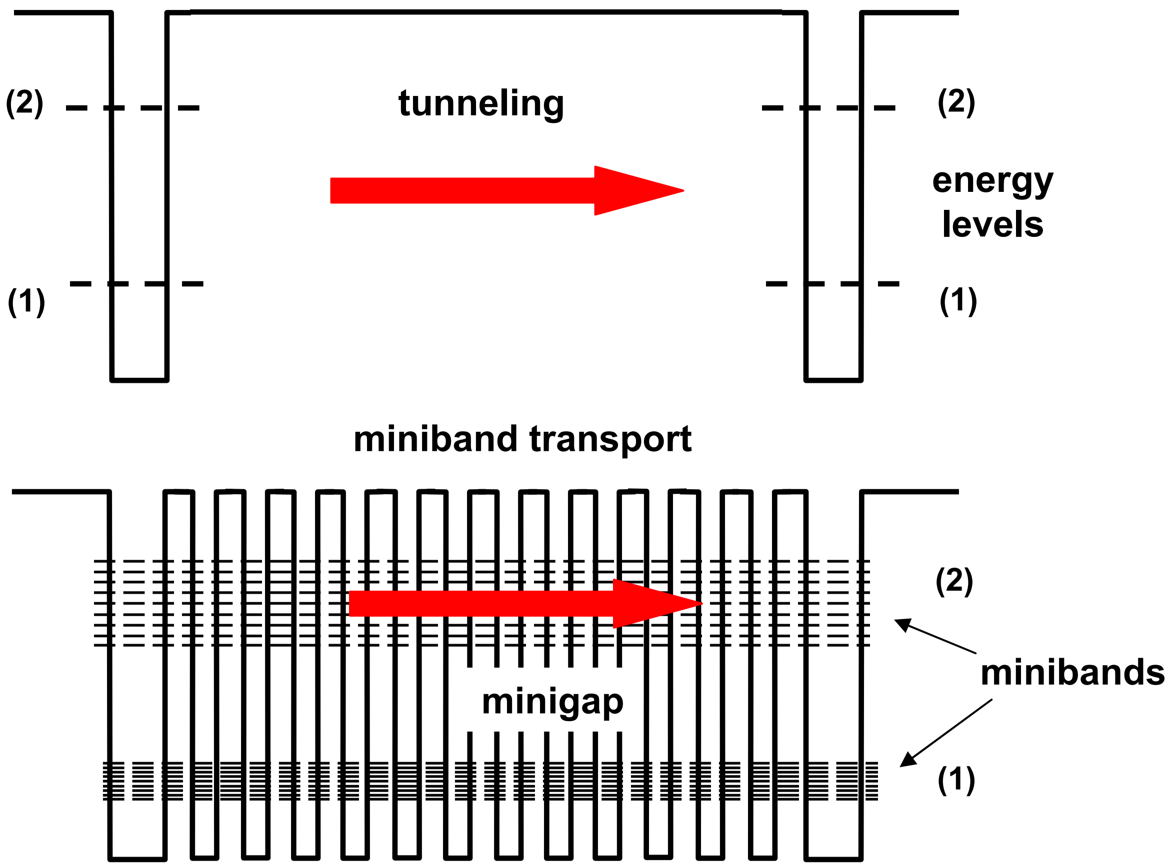


SL1

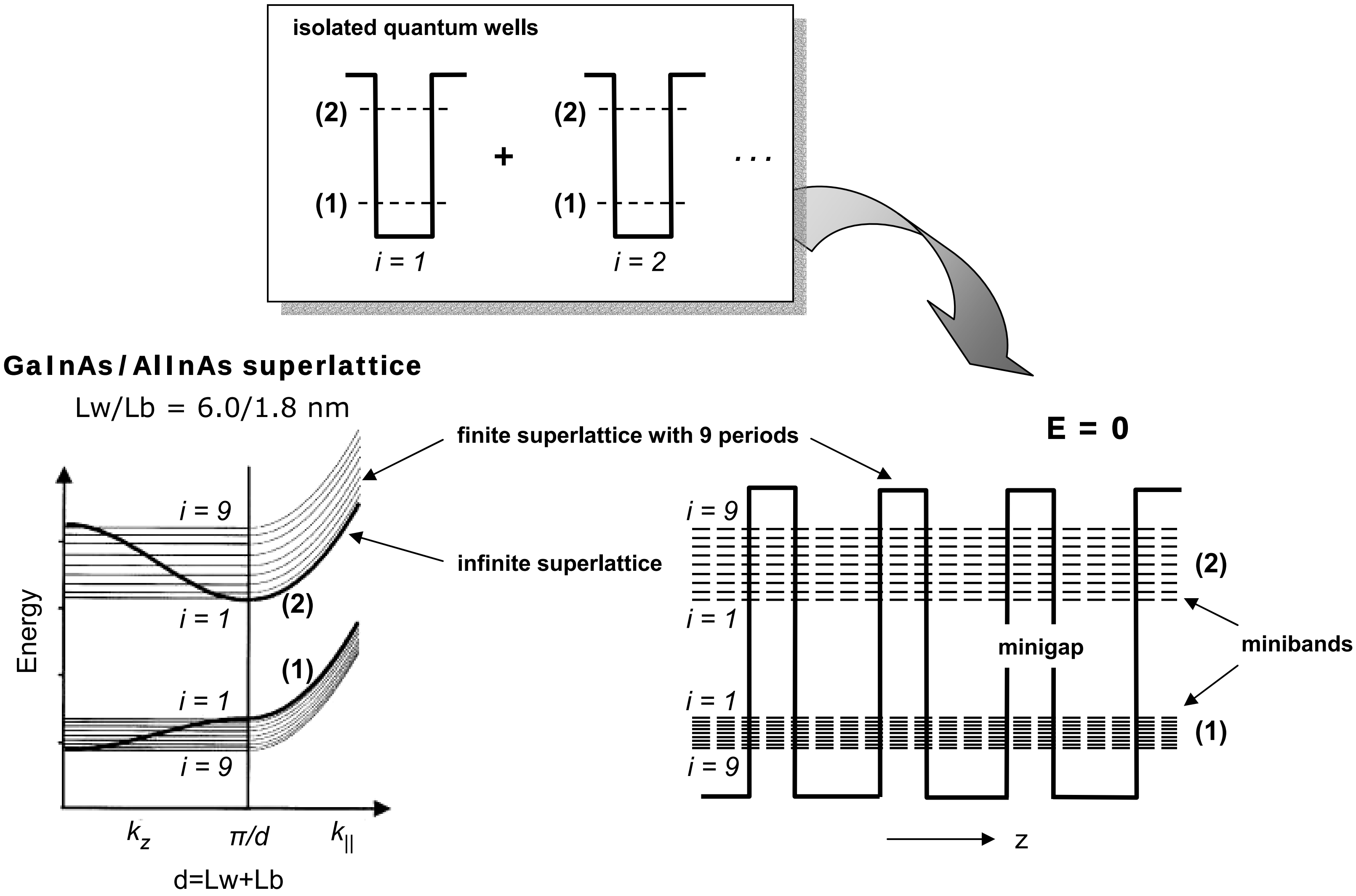
SL2

Continuum-to-continuum (superlattice QCL)

Laser design elements: Superlattice Injector



Laser design elements: Superlattice Injector


isolated quantum wells

GaInAs/AlInAs superlattice

Lw/Lb = 6.0/1.8 nm

finite superlattice with 9 periods

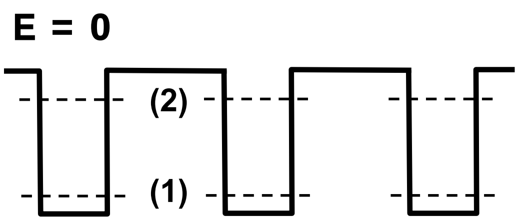
infinite superlattice

E = 0

minigap

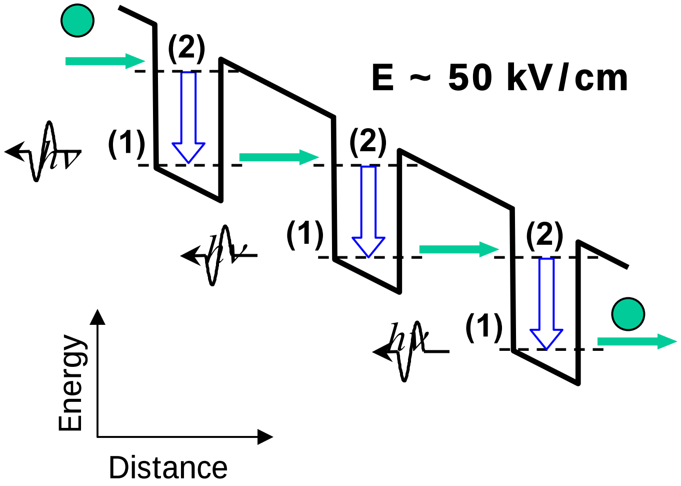
minibands

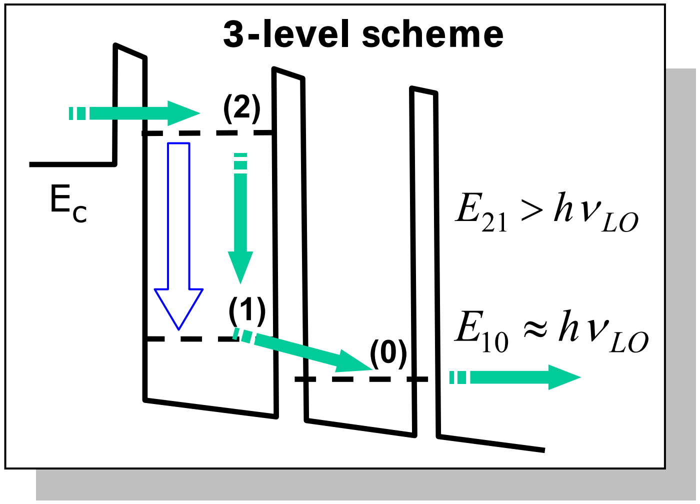
Monopolar transport offers electron recycling



Advantages of the cascaded scheme:

- *quantum efficiency in excess of 100%*
- *electrically uniform active region*
- *large confinement factor*
- *multy-wavelength operation*

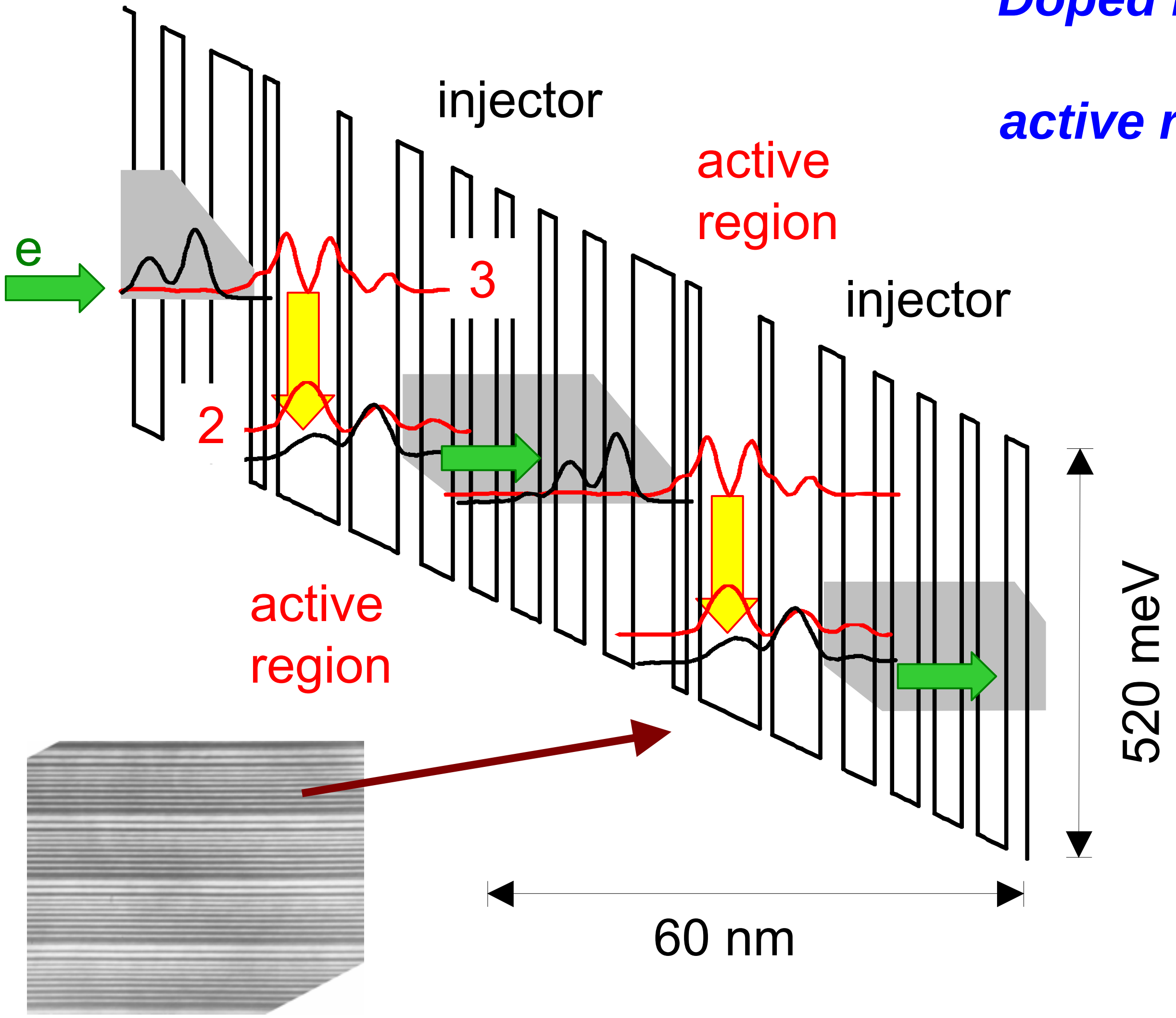




Intersubband-based QC-laser λ ~ 7.5 μm

Doped injectors separate

active regions electrically



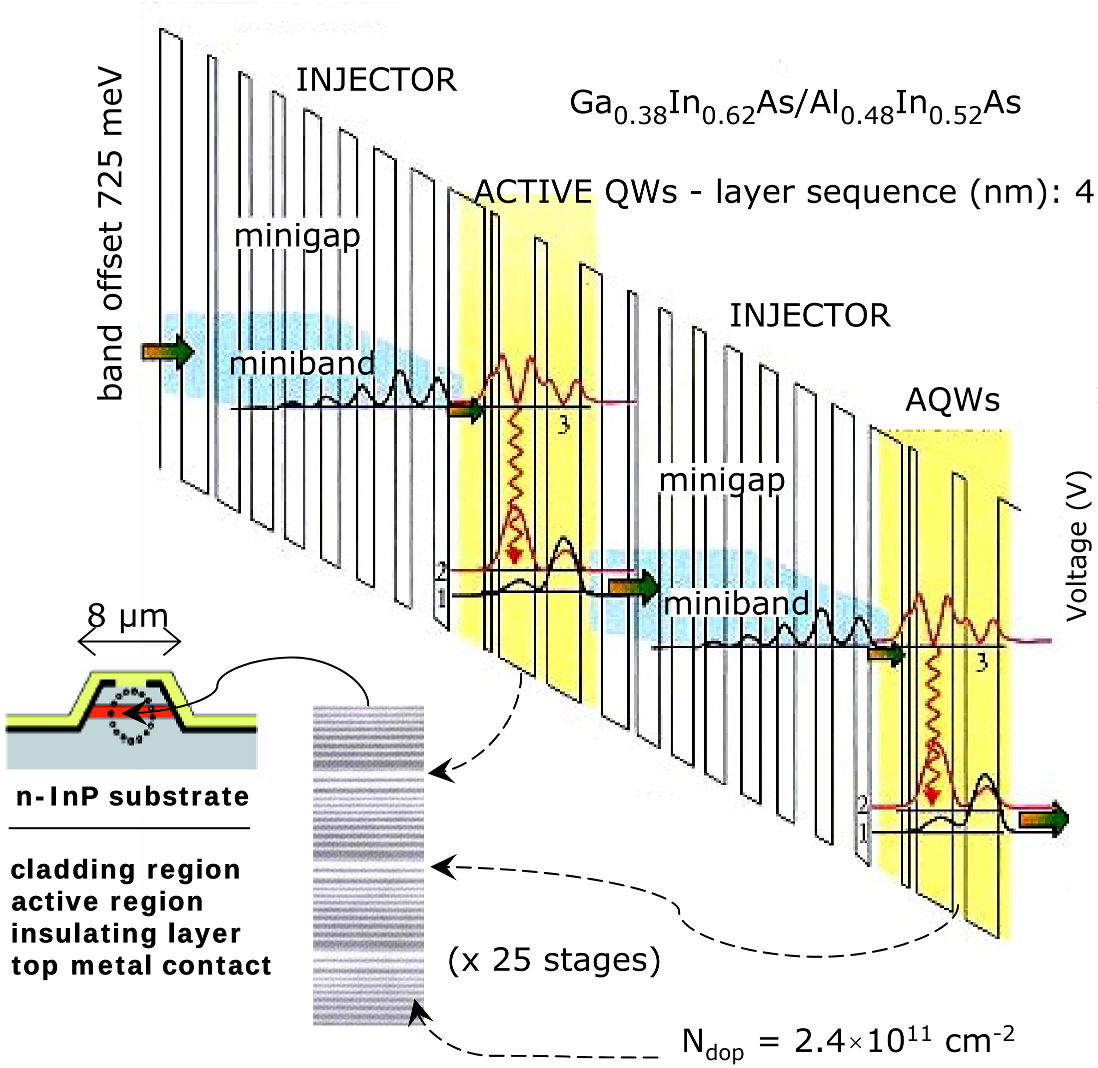
Courtesy of *Claire Gmachl* - Princeton University

Real laser design: three level QCL

$Ga_{0.38}In_{0.62}As/Al_{0.48}In_{0.52}As$

QW1 QW2 QW3

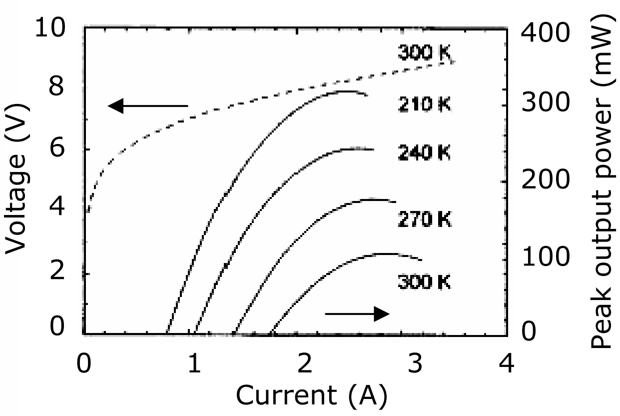
ACTIVE QWs - layer sequence (nm): 4.4/**0.9**/0.9/**4.8**/1.7/**4.4**/2.8



(x 25 stages)

$N_{dop} = 2.4 \times 10^{11}$ cm^{-2}

λ = 4.5 µm, pulsed



E_{32} = 280 meV
E_{21} = $h\nu_{LO}$ = 30 meV

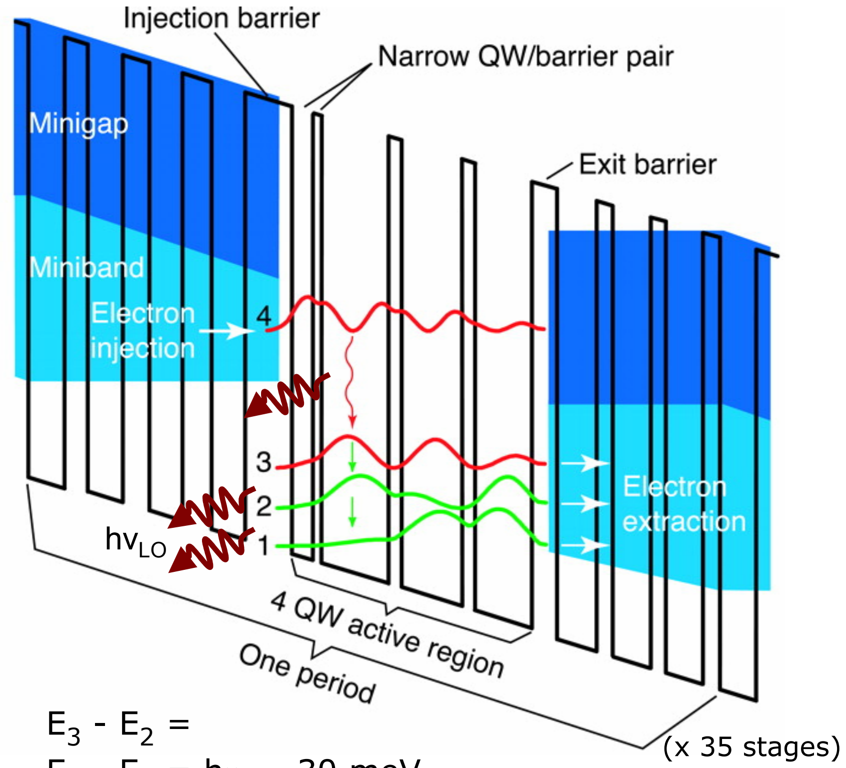
τ_{21} = 0.3 ps
τ_{32} = 2.6 ps
τ_{31} = 3.0 ps

F. Capasso *et al*. Physics Today **55**, 34 (May 2002)

R. Kohler *et al*. APL **76**, 1092 (Feb. 2000)

Related problem: Active Region Heating

Double-phonon depopulation scheme



$E_3 - E_2 =$

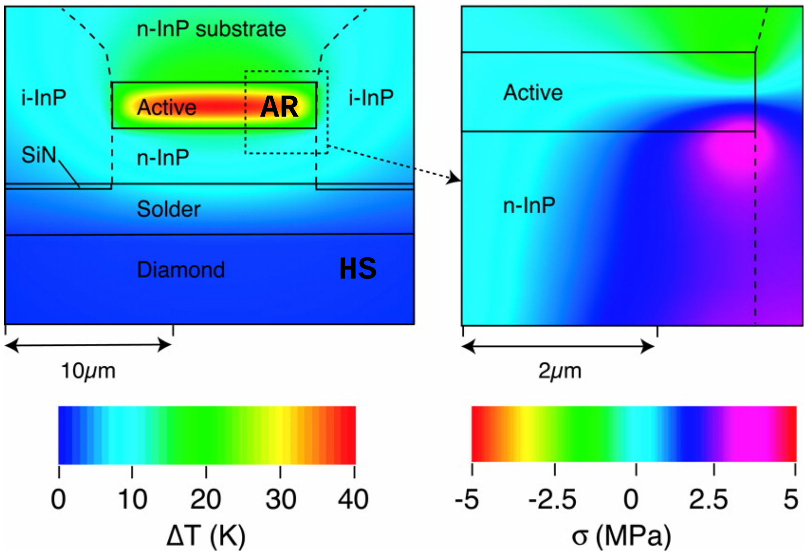
$E_2 - E_1 = h\nu_{LO} \sim 30$ meV

$E_4 - E_3 = 135$ meV ($\lambda = 9.1$ μm)

M. Beck *et al*. Science **295**, 301 (2002)

CW-RT Operation:

- buried stripe geometry
- epilayer-down mounting



$T_{AR} = T_{HS} + U \times J_{th}/G$; $\Delta T = T_{AR} - T_{HS}$

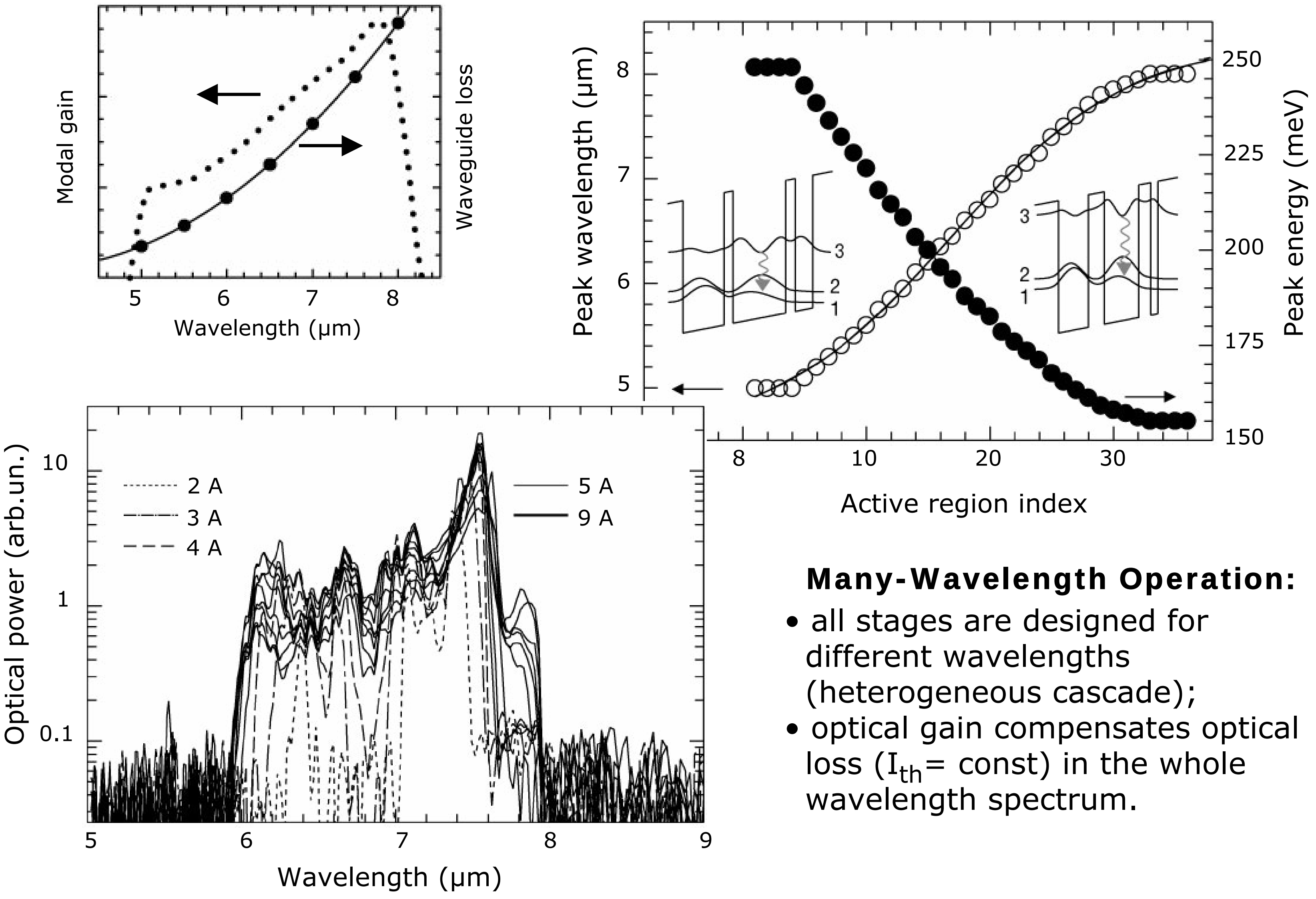
$J_{th} = J_0 \exp(T_{AR}/T_0)$

$J_0 = 560$ A/cm^2 ; $T_0 = 170$K

$J_{th} \sim 4.3$ kA/cm^2 (RT, CW)

$J_{th} \sim 3.1$ kA/cm^2 (RT, pulsed)

Ultra-broadband QCL

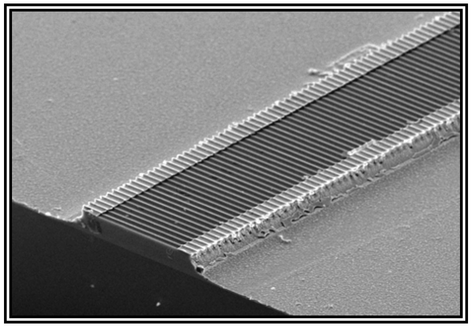


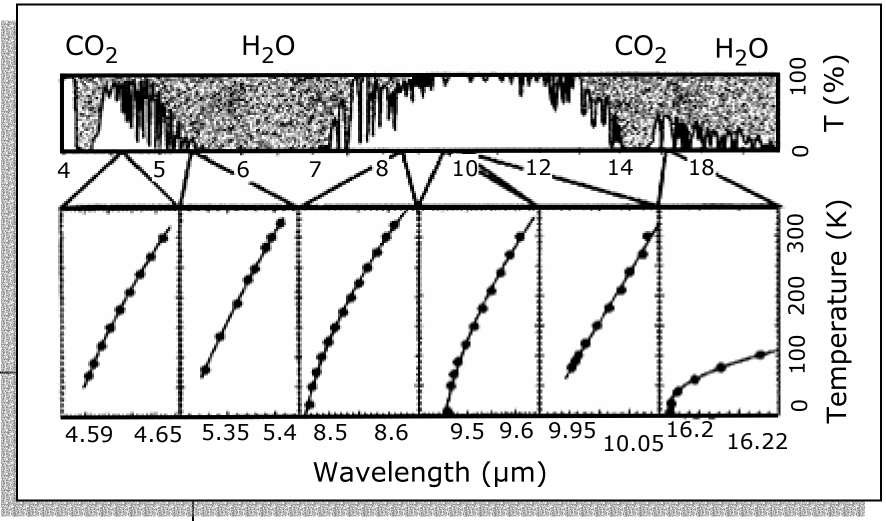
C. Gmachl *et al*. Nature **415**, 883 (Feb. 2002)

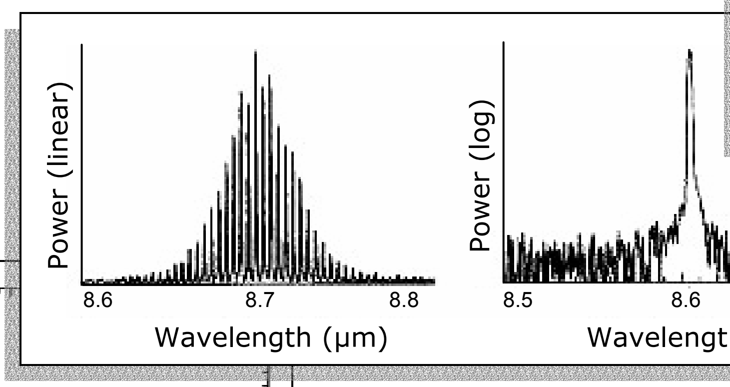
Many-Wavelength Operation:

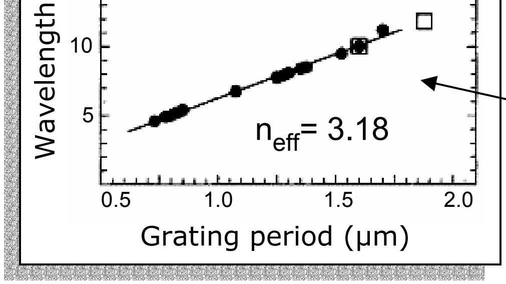
- all stages are designed for different wavelengths (heterogeneous cascade);
- optical gain compensates optical loss (I_{th}= const) in the whole wavelength spectrum.

DFB and Tunable QCL







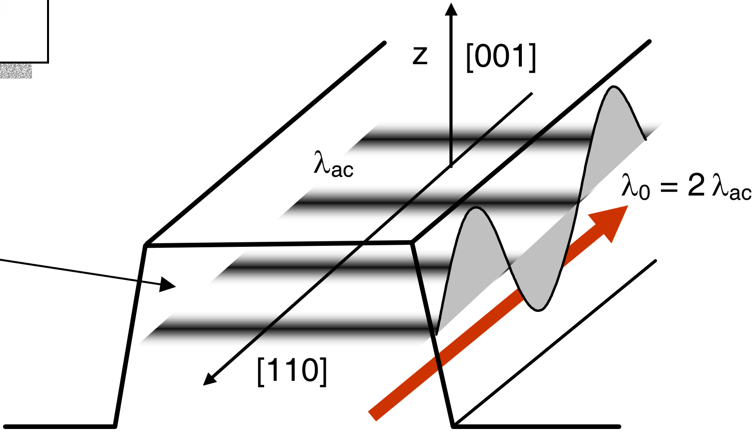


C. Gmachl *et al*. IEEE Journal QE **38**, 569 (2002)

DFB mechanisms:

- refractive index modulation;
- optical gain modulation.

$$\beta = \frac{2\pi}{\lambda} n_{eff} - \frac{i}{2}(\Gamma G - \alpha)$$



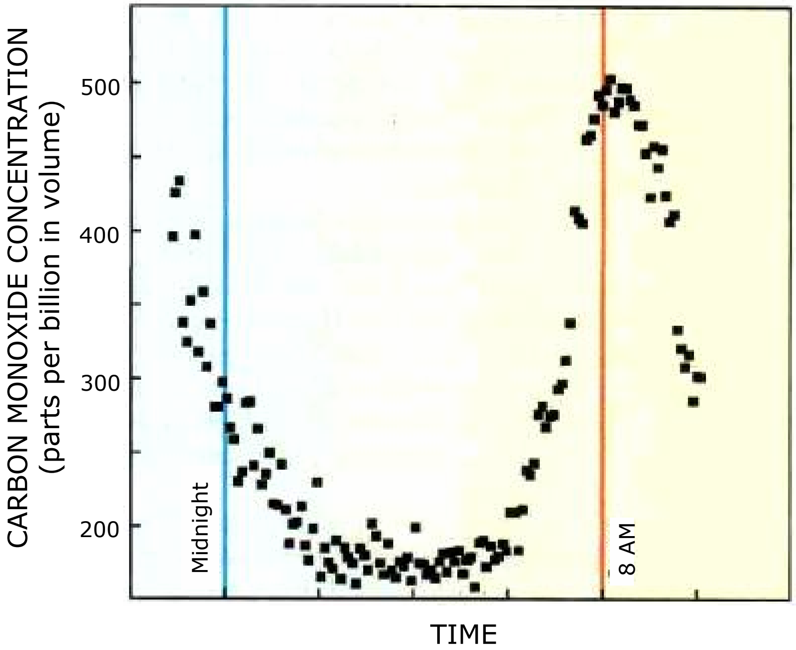
Piezo-Acoustic Wave

M.Kisin and S Luryi. Appl. Phys. Lett. **82**, 847 (2002)

Applications Example: Environmental Monitoring

Carbon monoxide concentrations in ambient air

(monitored at Rice University on March 2001, A. Kosterov *et al.*)



F. Capasso *et al*. Physics Today **55**, 34 (May 2002)

Mid IR spectrum is called molecular fingerprint region.

Two atmospheric transparency windows 3-5 μm and 8-13 μm lack water-vapor absorption and are particularly important for chemical-sensing applications.

Advantages of laser-based optical methods in trace-gas analysis include:

- noninvasive character,
- high sensitivity and selectivity,
- real-time detection.

Other exemplary applications:

- combustion diagnostics in the power and automobile industries, medical diagnostics,
- detection of explosives and drugs, chemical and biological weapons of mass destruction,
- military countermeasures as blinding the IR sensor of a heat-seeking missile,
- optical wireless communications in the eye-safe atmospheric transmission windows.

Recommended Literature

- J. Faist *et al*. Science (Apr. 1994), v.264, p.553.
- J. Faist *et al*. Nature (June 1997), v.387, p.777.
- C. Gmachl *et al*. Nature (Feb. 2002), v.415, p.883.
- M. Beck *et al*. Science (Jan. 2002), v.295, p.301.
- F. Capasso *et al*. IEEE Journal on Selected Topics in Quantum Electronics (Nov. 2000), v.6, p.931.
- J. Faist *et al*. IEEE Journal on Quantum Electronics (June 2002), v.38, p.533.
- F. Capasso *et al*. Physics Today (May 2002), v.55, p.34.