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

To provide excellent injection properties with minimum optical loss $\alpha$ and heating

To optimize optical confinement $\Gamma$

$g = \Gamma \cdot G - (\alpha_i + \alpha_m)$
Semiconductor Lasers: 2D vs. 3D confinement

**double-heterostructure laser**

**quantum well (QW) laser**

**3D joint DOS**

\[
\rho(hv) = \frac{1}{2\pi^2} \left( \frac{2m_r}{\hbar^2} \right)^{3/2} \sqrt{hv - E_g}
\]

\[
m_r^{-1} = m_c^{-1} - m_v^{-1} = m_c^{-1} + m_h^{-1}
\]

**2D joint DOS**

\[
\rho(hv) = \frac{m_r}{\pi \hbar^2}
\]
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
- $\delta$-like joint DOS provides for higher gain and better temperature stability
- Monopolar transport offers electron recycling

Interband and Intersubband lasing
Interband and Intersubband Lasing

**Interband Lasing Scheme**

- Bipolar laser: electron AND hole injection

**Intersubband Lasing Scheme**

- Monopolar transport offers electron recycling
  - 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
  - Hole transport is eliminated

Advantages:

- Electrical injection
- Optical pumping

Formula:

\[ E_{g, eff} \approx \hbar \nu \]

\[ E_g \gg \hbar \nu \]
\( \delta \)-like joint DOS provides for higher gain

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

- In intersubband lasers \( \delta \)-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

Bipolar laser

Monopolar laser

intersubband lasing

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

\[
\rho(E) = \frac{\rho(K)}{V_2(K) - V_1(K)} \rightarrow \rho_{2D}(E) = \frac{K}{\pi} \left| \frac{dE_2(K)}{dK} - \frac{dE_1(K)}{dK} \right|^{-1} = \frac{1}{\pi h^2} \left| \frac{1}{m_2} - \frac{1}{m_1} \right|^{-1} = \frac{m_e}{\pi h^2}
\]
Intersubband Kinetics

\[ \frac{n_2}{\tau_2} = \frac{n_1}{\tau_1} \quad (= J) \]
\[ \tau_1 < \tau_2 \implies n_2 > n_1 \]

Tunneling

Optical phonon emission

\[ h \nu \]

\[ h_{\nu_{LO}} \]

\[ R_r \]

\[ R_{nr} \]

3-level scheme

\[ E_{21} > h \nu_{LO} \]

\[ E_{10} \approx h \nu_{LO} \]

\[ M_{2-1}^2 \propto |K_2 - K_1|^{-1} \ll M_{1-0}^2 \propto |K_1 - K_0|^{-1} \]
Quantum Cascade Laser

**quantum cascade laser**

\[ E = 0 \]

\[ E \sim 50 \text{ kV/cm} \]

**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)

3QW, indirect (interwell)

4QW, direct transition

Double optical phonon resonance

Tunneling

Optical phonon resonance

Bound-to-continuum injectorless

Continuum-to-continuum (superlattice QCL)

QW

SL

SL1

SL2
Laser design elements: Superlattice Injector

miniband transport

minigap

minibands

tunneling

energy levels

(1) (1) (2) (2)
Laser design elements: Superlattice Injector

GaInAs/AlInAs superlattice
Lw/Lb = 6.0/1.8 nm

finite superlattice with 9 periods
infinite superlattice
isolated quantum wells
Advantages of the cascaded scheme:
• quantum efficiency in excess of 100%
• electrically uniform active region
• large confinement factor
• multy-wavelength operation

Monopolar transport offers electron recycling
Intersubband-based QC-laser $\lambda \sim 7.5$ $\mu$m

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

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

$\lambda = 4.5 \mu$m, pulsed

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

$\tau_{21} = 0.3$ ps  
$\tau_{32} = 2.6$ ps  
$\tau_{31} = 3.0$ ps

R. Kohler et al. APL 76, 1092 (Feb. 2000)
Related problem: Active Region Heating

Double-phonon depopulation scheme

\[ E_3 - E_2 = \hbar \nu_{LO} \approx 30 \text{ meV} \]
\[ E_2 - E_1 = \hbar \nu_{LO} \approx 30 \text{ meV} \]
\[ E_4 - E_3 = 135 \text{ meV} \ (\lambda = 9.1 \mu m) \]

CW-RT Operation:
- buried stripe geometry
- epilayer-down mounting

\[ J_{th} = J_0 \exp \left( \frac{T_{AR}}{T_0} \right) \]
\[ T_{th} \approx 560 \text{ A/cm}^2 \ ; \ T_0 = 170K \]
\[ J_{th} \approx 4.3 \text{ kA/cm}^2 \ (\text{RT, CW}) \]
\[ J_{th} \approx 3.1 \text{ kA/cm}^2 \ (\text{RT, pulsed}) \]
**Many-Wavelength Operation:**

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

DFB and Tunable QCL

DFB mechanisms:
- refractive index modulation;
- optical gain modulation.

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


Applications Example: Environmental Monitoring

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

- F. Capasso et al. Physics Today (May 2002), v.55, p.34.