Basic Concept of Lasers

- **Laser:**
  - Light Amplification by Stimulated Emission of Radiation

- **Basic elements:**
  - Gain media
  - Optical cavity

- **Threshold condition:**
  - Bias point where laser starts to “lase”
  - Gain (nearly) equals loss
L-I Curve of Semiconductor Lasers

- Distinctive threshold (at least in classical lasers)
- Semiconductor laser is a forward-biased p-n junction, so mainly a current-biased device
- Threshold current:
  - Minimum current at which the laser starts to “lase”
- Quantum efficiency
  - “Differential” electrical-to-optical conversion efficiency, i.e., how many photons generated by injected electrons beyond threshold
- Wall-plug efficiency
  - Total electrical-to-optical conversion efficiency

![Graph showing L-I curve for semiconductor lasers]

“Edge-Emitting” Semiconductor Lasers

- g: gain coefficient [cm\(^{-1}\)]
- Light amplification: \( I(z) = I_0 e^{gz} \)
  - \( \Gamma \): confinement factor (fraction of energy in gain media)
  - Threshold condition:
    - Round-trip gain = 1
    - \( e^{\Gamma g (\alpha_l + \alpha_m) L} R_0 R_1 e^{\Gamma g (\alpha_l + \alpha_m) L} R_2 = 1 \)
    - \( g = g_{th} = \frac{\alpha_l}{\Gamma} + \frac{1}{2\Gamma L} \ln \left( \frac{1}{R_0 R_2} \right) = \frac{\alpha_l + \alpha_m}{\Gamma} \)
    - \( \alpha_l \): intrinsic loss
    - \( \alpha_m = \frac{1}{2L} \ln \left( \frac{1}{R_0 R_2} \right) \): mirror loss (i.e., output light)
Modern Lasers

- Optical cavity does not necessarily consist of mirrors

### Generic Description of Optical Cavity

**Quality Factor:**

\[ Q = \frac{\text{Energy Stored}}{\text{Energy Dissipated per Cycle}} \]

\[ Q = \frac{\omega}{\Delta \omega} \]

\[ \Delta \omega = \frac{1}{\tau_p} \]

\( \tau_p \): photon lifetime [sec]

\[ \frac{1}{\tau_p} = \frac{\alpha c}{n} \]

\( \alpha \): loss rate per cm

\( 1 / \tau_p \): loss rate per sec

\[ Q = \omega \tau_p \]
**Photon Lifetime and Spectral Width**

Decay of optical energy when input is turned off (ring-down measurement):

\[ I(t) = I_0 e^{-t/\tau_p} \quad \text{for} \quad t \geq 0 \]

Electrical (optical) field:

\[ E(t) = E_0 e^{i\omega t} e^{-t/2\tau_p} \quad \text{for} \quad t \geq 0 \]

Frequency domain response (Fourier transform):

\[ H(\omega) = \frac{1}{j(\omega - \omega_0) + 1/2\tau_p} \]

FWHM of \( |H(\omega)|^2 \):

\[ \Delta \omega = \frac{1}{\tau_p} \]

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**Threshold Condition of Generic Lasers**

Gain = Loss
(rate of gain = rate of loss)

\[ \Gamma g_{th} = \frac{c}{n} = \frac{1}{\tau_p} = \frac{\omega}{Q} \]

\[ g_{th} = \frac{\omega n}{Q \Gamma_c} \]

Quantum efficiency:

\[ \eta = \frac{\alpha_m}{\alpha_m + \alpha_i} = \frac{Q_{rad}^{-1}}{Q_{rad}^{-1} + Q_{loss}^{-1}} = \frac{Q_{rad}^{-1}}{Q^{-1}} \]

\[ \eta = \frac{Q}{Q_{rad}} \]
Typical Q of Semiconductor Laser

Edge-emitting laser:
\[ L = 100 \mu m, \ R = 30\%, \ \omega \sim 100 \text{THz}, \ \tau_p \sim 1 \text{ps}, \ Q \sim 600 \]

Vertical Cavity Surface-Emitting Laser (VCSEL)
\[ L = 1 \mu m, R = 99\%, \ Q \sim 700 \]

Microdisk (Whispering Gallery Mode or WGM) Laser
\[ Q \sim 1000 \] (up to \(10^{11}\) possible in low loss materials)

Photonic crystal laser: \( Q \sim 1000 \) (up to \(10^6\) possible)

Metal cavity laser (plasmonic laser): \( Q \sim 10 \text{ to } 100 \)

Gain Cross-Section

Gain cross-section (instead of gain coefficient) is often used to measure the gain in gas or solid-state lasers:
\[ \sigma: \ [\text{cm}^2] \]
Gain cross-section is related to gain by:
\[ g = N \sigma \]
where \( N \) is concentration of active molecules

For comparison, in semiconductor lasers:
\[ g \sim 100 \text{ cm}^{-1} \]
\[ N \sim 10^{18} \text{ cm}^{-3} \] (typical electron concentration at threshold)
\[ \sigma \sim 10^{-16} \text{ cm}^2 \] (\(=(0.1 \text{nm})^2\))

Note: more precise relation between gain and carrier concentration will be discussed in future lectures