EE 232 Lightwave Devices
Lecture 2: Basic Concepts of Lasers

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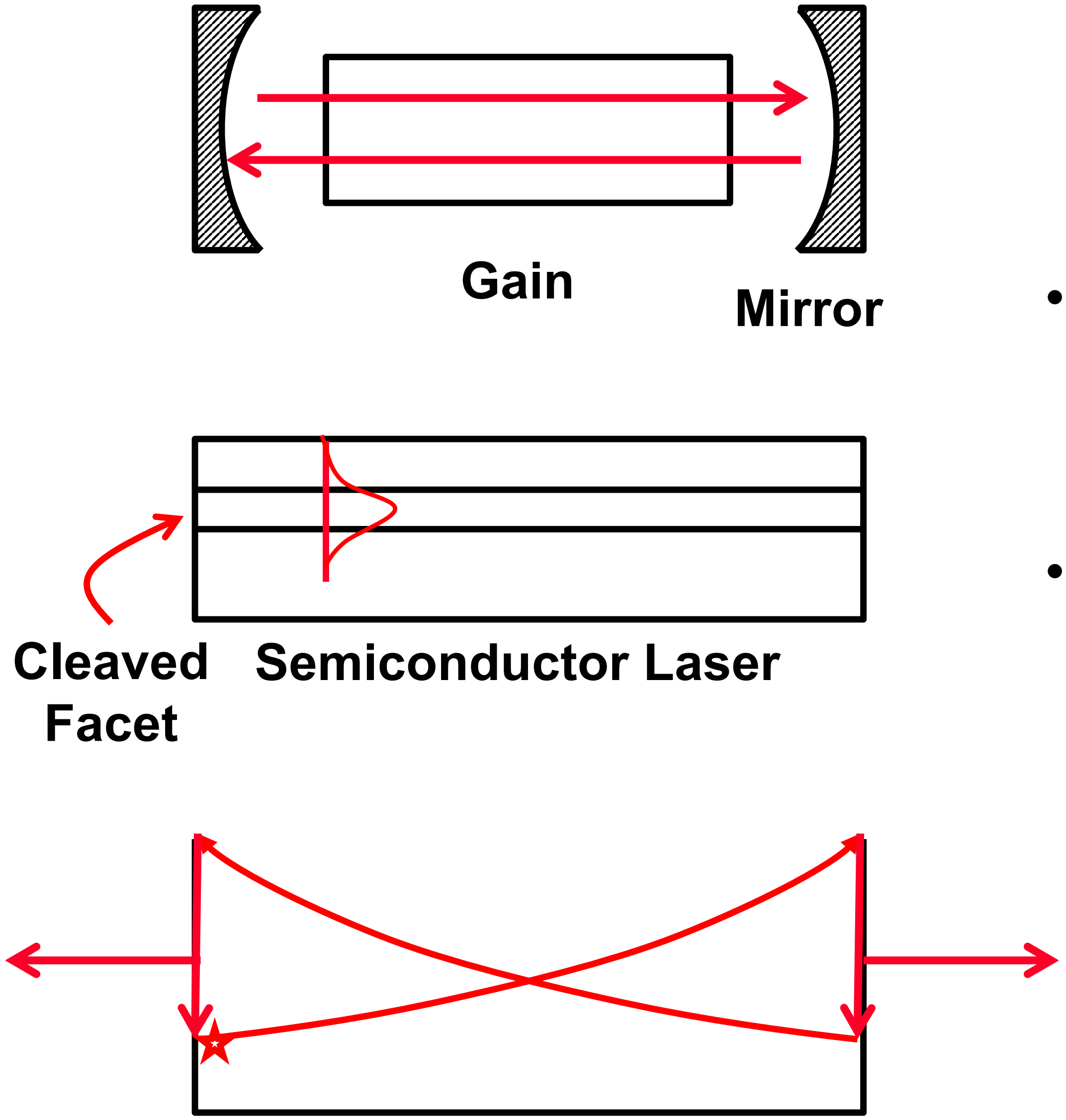
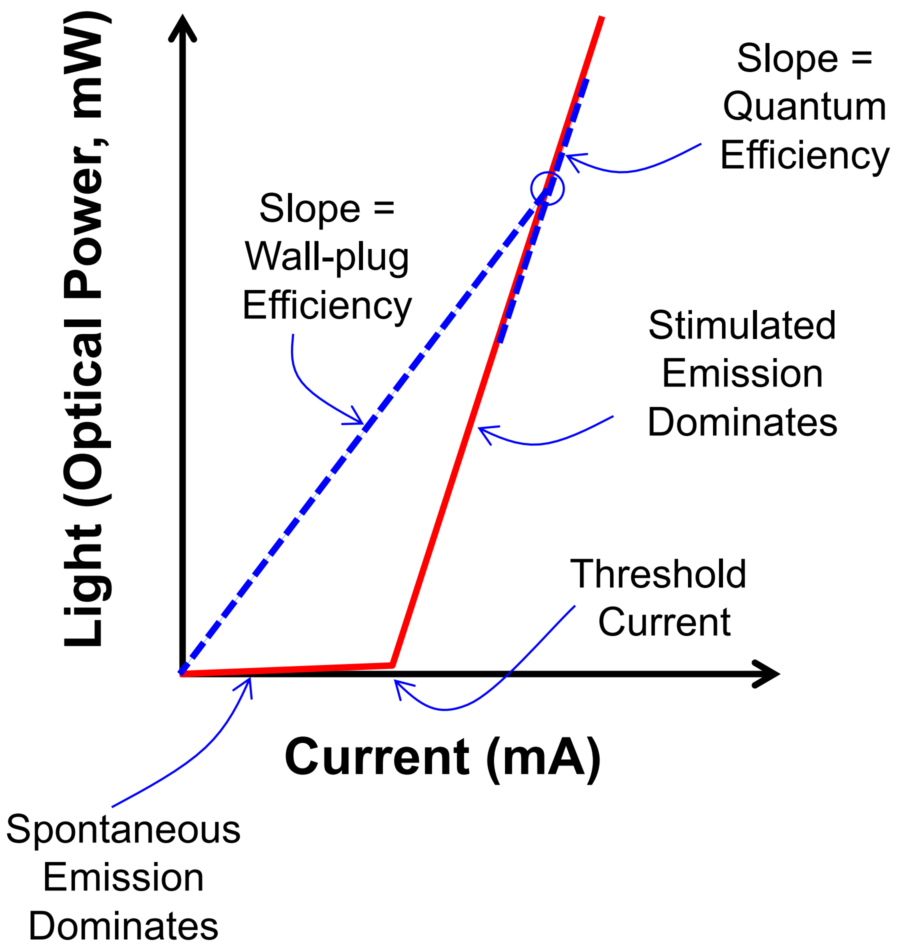
Basic Concept of Lasers



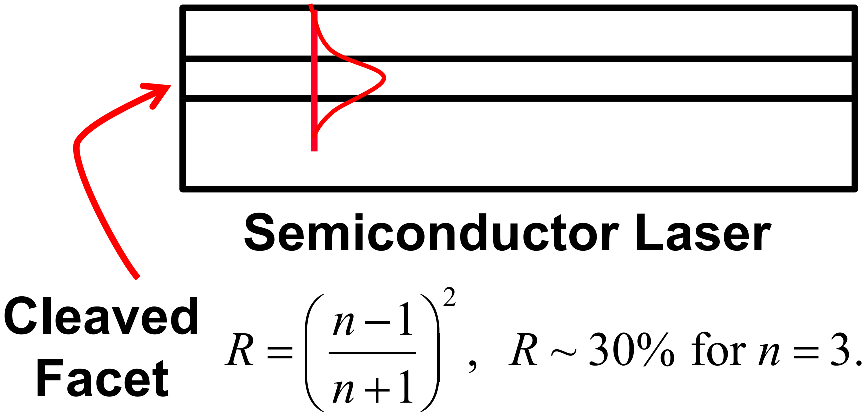
- **Laser:**
  - **Light Amplification by Stimulated Emission of Radiation**
- **Basic elements:**
  - **Gain media**
  - **Optical cavity**
- **Threshold condition:**
  - **Bias point where laser starts to “lase”**
  - **Gain (nearly) equals loss**

L-I Curve of Semiconductor Lasers

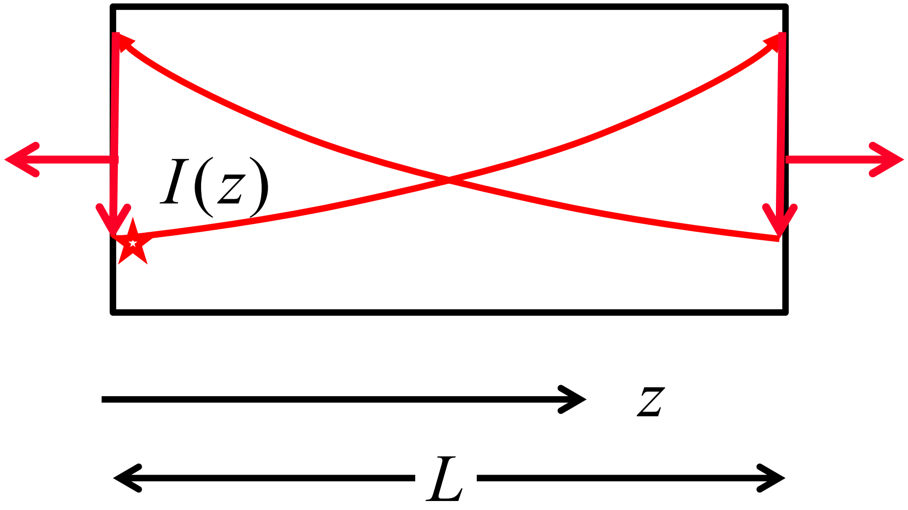


- Distinctive threshold (at least in classical lasers)
- Semiconductor laser is a forward-biased p-n junction, so mainly a current-biased device
- Threshold current :
  - Minimum current at which the laser starts to “lase”
- Quantum efficiency
  - “Differential” electrical-to-optical conversion efficiency,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

"Edge-Emitting" Semiconductor Lasers



$$R = \left(\frac{n-1}{n+1}\right)^2, \quad R \sim 30\% \text{ for } n = 3.5$$



g : gain coefficient [cm^{-1}]

Light ampflication: $I(z) = I_0 e^{\Gamma g z}$

Γ: confinement factor

(fraction of energy in gain media)

Threshold condition:

Round-trip gain = 1

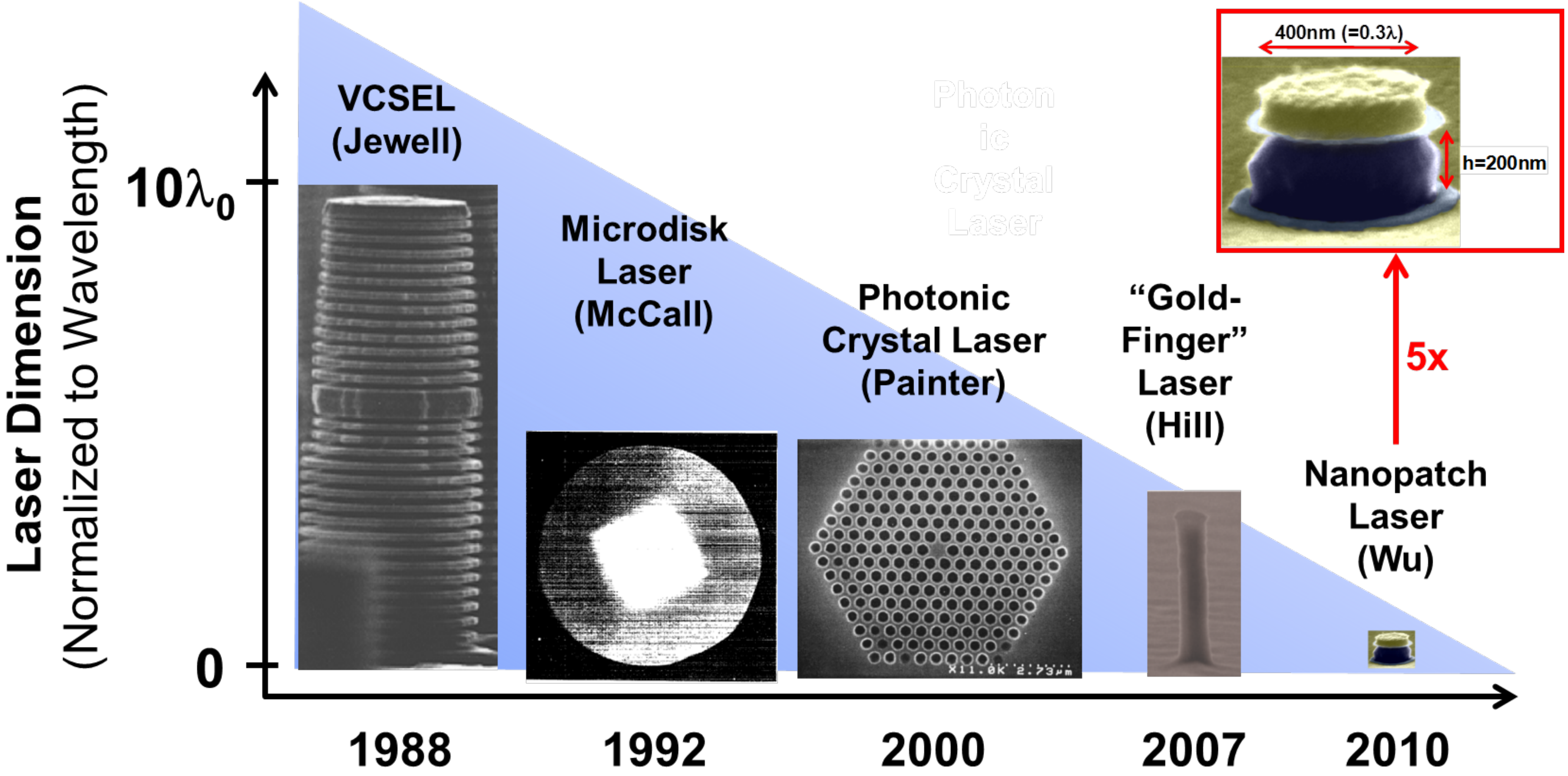
$$e^{\Gamma g L - \alpha_i L} R_1 e^{\Gamma g L - \alpha_i L} R_2 = 1$$

$$g = g_{th} = \frac{\alpha_i}{\Gamma} + \frac{1}{2\Gamma L} \ln\left(\frac{1}{R_1 R_2}\right) = \frac{\alpha_i + \alpha_m}{\Gamma}$$

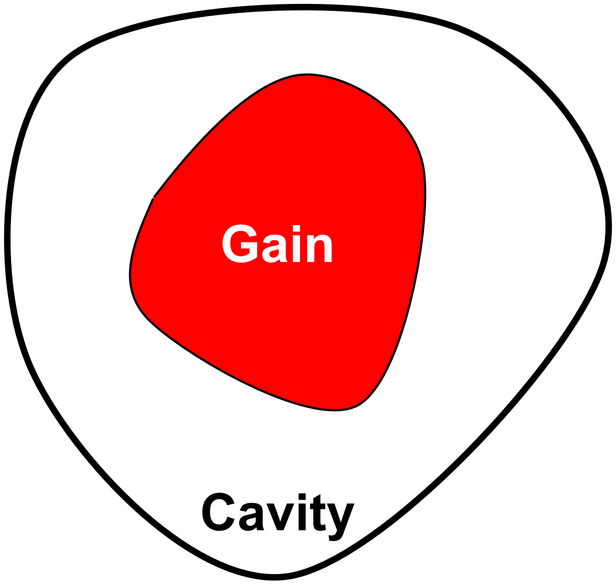
$$\begin{cases} \alpha_i \ : \text{intrinsic loss} \\ \alpha_m = \dfrac{1}{2L} \ln\left(\dfrac{1}{R_1 R_2}\right) : \quad \text{mirror loss (i.e., output light)} \end{cases}$$

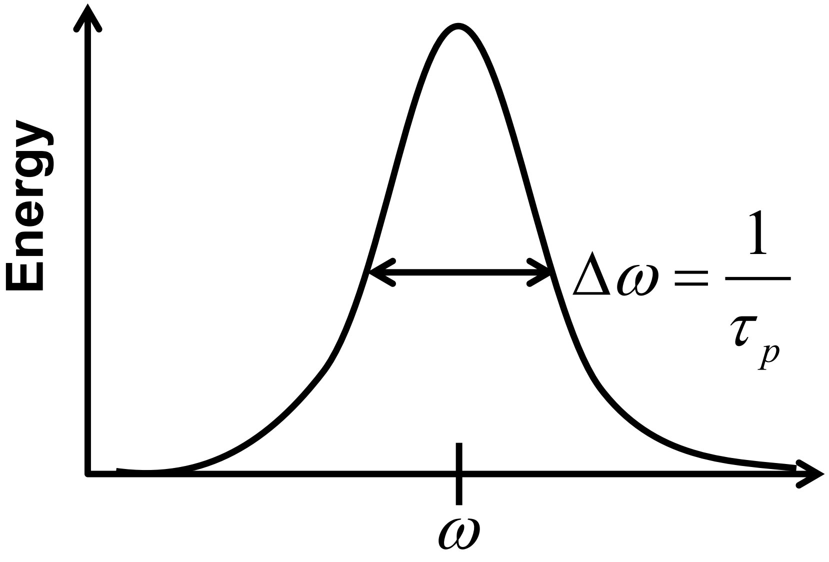
Modern Lasers

- Optical cavity does not necessarily consist of mirrors



Generic Description of Optical Cavity





Quality Factor:

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

$$Q = \frac{\omega}{\Delta\omega}$$

$$\Delta\omega = \frac{1}{\tau_p}$$

τ_p : photon lifetime [sec]

$$\frac{1}{\tau_p} = \alpha \frac{c}{n} \qquad \left(\begin{array}{l} \alpha\text{: loss rate per cm} \\ 1/\tau_p\text{: loss rate per sec} \end{array} \right)$$

$$\boxed{Q = \omega\tau_p}$$

Photon Lifetime and Spectral Width

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

$$I(t) = I_0 e^{-t/\tau_p} \qquad \text{for } \; t \geq 0$$

Electrical (optical) field:

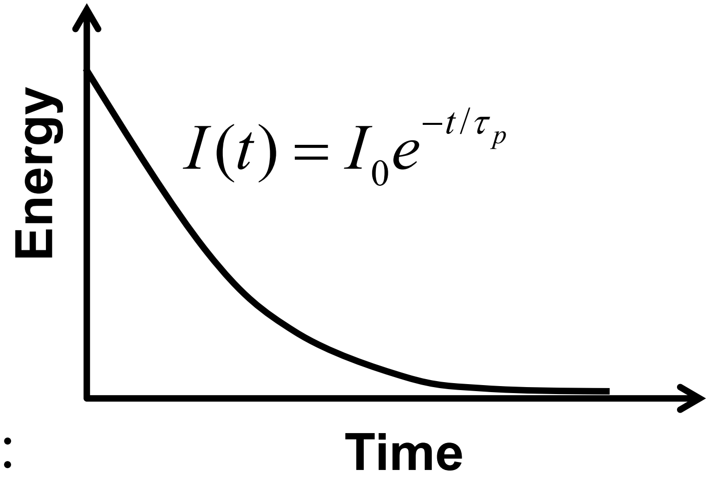
$$E(t) = E_0 e^{j\omega_0 t} e^{-t/2\tau_p} \qquad \text{for } \; t \geq 0$$

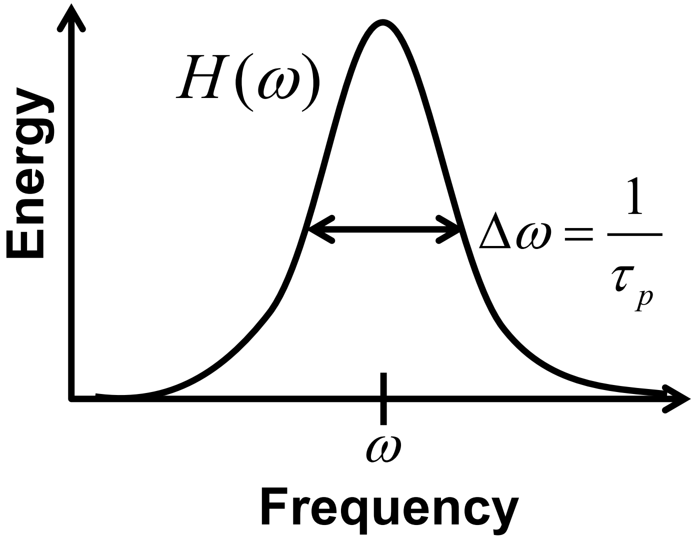
Frequency domain response (Fourier transform):

$$H(\omega) = \int_0^{\infty} e^{j\omega_0 t} e^{-t/2\tau_p} e^{-j\omega t} dt = \frac{1}{j(\omega - \omega_0) + 1/2\tau_p}$$

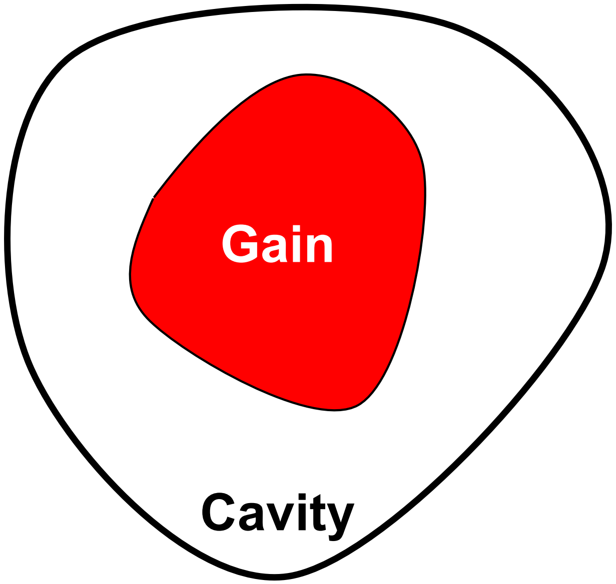
$$\text{FWHM of } \left|H(\omega)\right|^2 : \quad \omega - \omega_0 = \pm \frac{1}{2\tau_p}$$

$$\boxed{\Delta\omega = \frac{1}{\tau_p}}$$





Threshold Condition of Generic Lasers

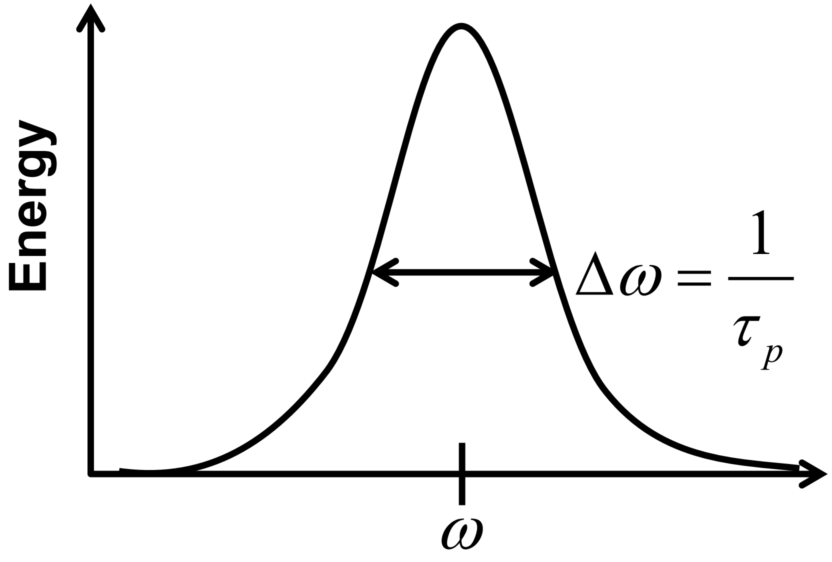


Gain = Loss

(rate of gain = rate of loss)

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

$$\boxed{g_{th}=\frac{\omega}{Q}\frac{n}{\Gamma c}}$$



$$\Delta\omega=\frac{1}{\tau_p}$$

Quantum efficiency:

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

$$\boxed{\eta=\frac{Q}{Q_{rad}}}$$

Typical Q of Semiconductor Laser

Edge-emitting laser:

$L = 100\mu m,\ \ R = 30\%,\ \ \omega \sim 100THz\ ,\ \tau_p \sim 1ps,\ \ Q \sim 600$

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): $Q \sim 10$ 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:

σ : $[\mathrm{cm}^2]$

Gain cross-section is related to gain by:

$g = N\sigma$

where N is concentration of active molecules

For comparison, in semiconductor lasers:

$g \sim 100\ \mathrm{cm}^{-1}$

$N \sim 10^{18}\ \mathrm{cm}^{-3}$ (typical electron concentration at threshold)

$\sigma \sim 10^{-16}\ \mathrm{cm}^2\ (= (0.1\mathrm{nm})^2\ )$

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