EE 232 Lightwave Devices
Lecture 2: Basic Concepts of Lasers
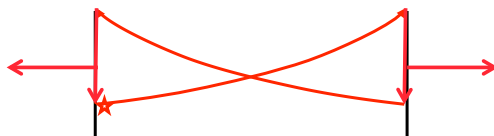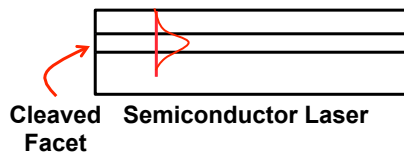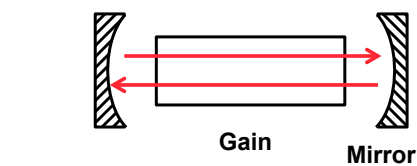
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Basic Concept of Lasers

Gain   **Mirror**

Cleaved   Semiconductor Laser
Facet

- **Laser:**
  - **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation

- **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
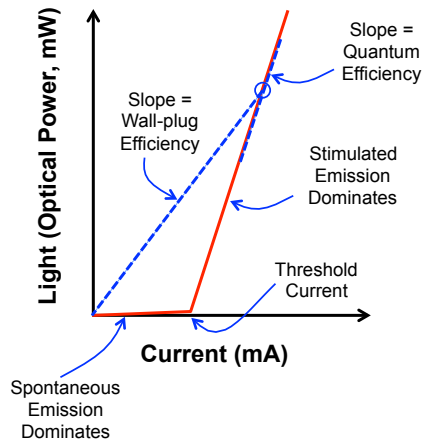

- **Distinctive threshold (at least in classical lasers)**

- **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**
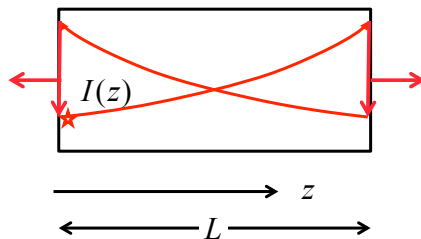 - **Total electrical-to-optical conversion efficiency**

"Edge-Emitting" Semiconductor Lasers

Semiconductor Laser
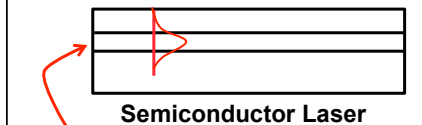
Cleaved Facet $R = \left(\dfrac{n-1}{n+1} \right)^2$, $R \sim 30\%$ for $n = 3.5$

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

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

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

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

Modern Lasers

- **Optical cavity does not necessarily consist of mirrors**

Laser Dimension (Normalized to Wavelength)

$10\lambda_0$

0

VCSEL (Jewell)

Microdisk Laser (McCall)

Photonic Crystal Laser (Painter)

"Gold-Finger" Laser (Hill)

Nanopatch Laser (Wu)

400nm (=0.3λ)

h=200nm

5x

1988   1992   2000   2007   2010
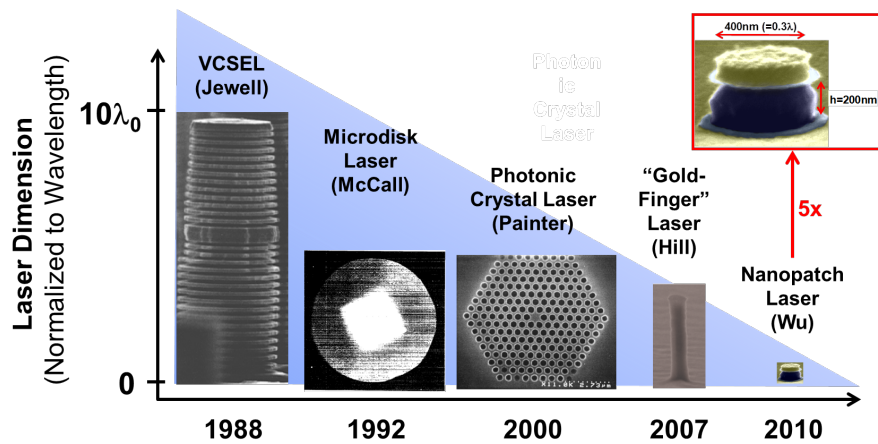
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Generic Description of Optical Cavity

Gain

Cavity

Energy

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

ω
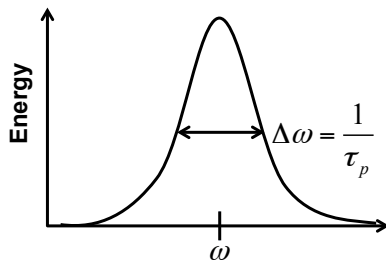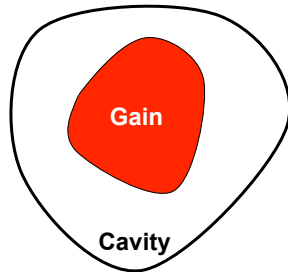
Quality Factor:

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

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

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

τ_p : photon lifetime [sec]

$$\frac{1}{\tau_p} = \alpha\frac{c}{n} \qquad \begin{pmatrix} \alpha: \text{loss rate per cm} \\ 1/\tau_p: \text{loss rate per sec} \end{pmatrix}$$

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

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Photon Lifetime and Spectral Width

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

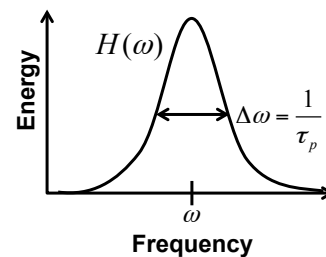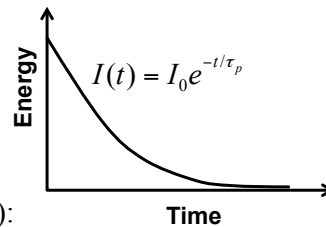$$I(t) = I_0 e^{-t/\tau_p} \quad \text{for } t \geq 0$$

Electrical (optical) field:

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

Frequency domain response (Fourier transform):

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

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

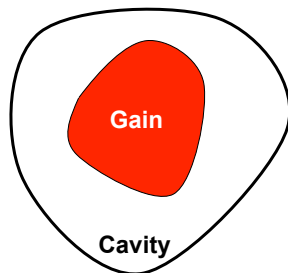$$\boxed{\Delta\omega = \frac{1}{\tau_p}}$$

$I(t) = I_0 e^{-t/\tau_p}$

Energy / Time

$H(\omega)$

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

Energy / ω / Frequency

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Threshold Condition of Generic Lasers

Gain
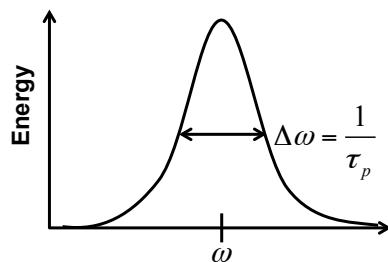
Cavity

Energy

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

ω

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

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

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

Quantum efficiency:

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

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

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Typical Q of Semiconductor Laser

Edge-emitting laser:

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

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): $Q \sim 10$ to 100

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Gain Cross-Section

Gain cross-section (instead of gain coefficient) is often used
to measure the gain in gas or solid-state lasers:

$\sigma: \ [cm^2]$

Gain cross-section is related to gain by:

$g = N\sigma$

where N is concentration of active molecules

For comparison, in semiconductor lasers:

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

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

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

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

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