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

Light (Optical Power, mW) vs. Current (mA)

Spontaneous Emission Dominates

Stimulated Emission Dominates

Slope = Wall-plug Efficiency

Slope = Quantum Efficiency

Threshold Current

“Edge-Emitting” Semiconductor Lasers

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

Light amplification: $I(z) = I_0 e^{g z}$

$\Gamma$ : confinement factor

(fraction of energy in gain media)

Threshold condition:
Round-trip gain = 1

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

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

$\alpha_t$ : intrinsic loss
$\alpha_m = \frac{1}{2 L} \ln \left( \frac{1}{R_1 R_2} \right)$ : mirror loss

(i.e., output light)

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

Semiconductor Laser

Cleaved Facet

$I(z)$

$L$ $z$

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Modern Lasers

- Optical cavity does not necessarily consist of mirrors

![Diagram showing laser dimension (normalized to wavelength) from 1988 to 2010 with various cavity designs such as VCSEL (Jewell), Microdisk Laser (McCall), Photonic Crystal Laser (Painter), and Gold-Finger Laser (Hill).]

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]

\[ \frac{1}{\tau_p} = \frac{\alpha c}{n} \quad \left( \alpha: \text{loss rate per cm} \right) \quad \frac{1}{\tau_p}: \text{loss rate per sec} \]

\[ Q = \omega \tau_p \]
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:

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

Frequency domain response (Fourier transform):

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

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)

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

\[ g_{\text{th}} = \frac{\omega}{Q \Gamma c} \]

Quantum efficiency:

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

\[ \sigma: [cm^2] \]

Gain cross-section is related to gain by:

\[ g = N\sigma \]

where \( N \) is concentration of active molecules

For comparison, in semiconductor lasers:

\[ g \sim 100 \text{ cm}^{-1} \]

\[ N \sim 10^{18} \text{ cm}^{-3} \] (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*