EE529 Semiconductor Optoelectronics

Semiconductor Lasers

1. Optical gain spectrum
2. Laser threshold, power and efficiency
3. Modulation characteristics
4. Advanced laser structures

Reading: Liu, Sec. 13.3-13.4, 13.9-13.10
Ref: Bhattacharya, Sec. 6.7, 7.2, 7.13; Liu, Sec. 4.3, 5.1
Laser Operation

Lasing process in a ruby laser

Process:

1. Population inversion — Through optical pumping or carrier injection.
2. Seed photons — From spontaneous emission and initiate the stimulated emission process.
3. Optical cavity — Resonant enhancement and define the output wavelength.
   → Steady state.
5. Output coupling — Let some of the photons out at each round trip.
Basic Semiconductor Laser Structure

**Figure 1:**
- Diagram showing the basic structure of a semiconductor laser, including energy bands, electron and hole distributions, and an edge-emitting laser diode with dimensions.
- Electrical current and voltage diagram illustrating the operation.

**Figure 2:**
- Schematic of a semiconductor laser, highlighting key regions such as the active region, inversion layer, and electrode connections.
- Cross-sectional view of a laser diode, showing the cleaved surface mirror and GaAs layers.

**Figure 3:**
- Photograph of an edge-emitting laser diode, labeled with dimensions and showing the device with a scale of 500 μm.
Different Regimes of Operation

Pumped electrically or optically until population inversion happened.
→ Emission > Absorption.
Optical Gain Spectrum

Optical gain coefficient $g$: Fractional change in the light power (or intensity) per unit distance

$$g(v) = \frac{\sqrt{2}(m^*_{r})^{3/2} c^2}{n^2 \hbar^2 v^2 \tau_{sp}} (\hbar v - E_g)^{1/2} \left[ f_c(E_2) - f_v(E_1) \right]$$

Laser medium

- $F_E$
- $\Delta$

$\Delta E_F$

$N/N_{tr} = 3.0$

$\alpha_0$

$g_{max}$

$h\nu_{max} - E_g$

$N/N_{tr}$

$\Delta E_g$

$g_{max}$

$E_g$

$E_{1}$

$E_{2}$
Threshold Gain $g_{th}$

Shown on the right is a typical output power-Injection current characteristics of a laser diode.
When does lasing happen?
Steady-state condition: Laser power is constant
→ Round-trip gain = Round-trip loss

Where does the loss come from?
Reflection loss at the mirrors. Losses in the cavity medium (scattering at defects, absorption by impurities, absorption by free carriers …)

$$P_f = P_i R_1 R_2 \exp[g(2L)] \exp[-\alpha(2L)]$$

$\alpha$ : Loss coefficient of the laser medium

$$P_f = P_i \rightarrow g_{th} = \alpha + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right)$$
Threshold Current and Efficiency

Laser diode active layer thickness = d

Determine $N_{th}$ from the gain spectrum

$$J_{th} = \frac{edN_{th}}{\eta_{inj}\tau_s} \quad \text{or} \quad J_{th} = \frac{edR_{sp}(N_{th})}{\eta_{inj}\eta_i}$$

Above threshold, under steady state,

$$P_{out} = \eta_i \eta_{inj} \frac{hv}{e} (I - I_{th}) \frac{(1/2L)\ln(1/R_1R_2)}{\alpha + (1/2L)\ln(1/R_1R_2)}$$

External quantum efficiency

$$\eta_e = \frac{d(P_{out}/hv)}{d(I - I_{th})/e} = \eta_i \eta_{inj} \frac{(1/2L)\ln(1/R_1R_2)}{\alpha + (1/2L)\ln(1/R_1R_2)}$$

Slope efficiency

$$\eta_s = \frac{dP_{out}}{VdI} = \eta_e \frac{hv}{eV}$$

Power conversion efficiency

$$\eta_c = \frac{P_{out}}{VI} = \eta_e \frac{hv}{eV} \left(1 - \frac{I_{th}}{I}\right)$$

$P_o = \text{Lasing output power}$

$\eta_e \propto N_{ph}$

Slope represents efficiency
Exercise: Threshold Current Density of a GaAs Laser

Calculate the threshold current of a GaAs laser with an undoped active region of width $d = 0.2 \, \mu m$ starting from $g(E)$ and $R_{sp}(E)$:

$$g(E) = 3 \times 10^3 \frac{(E - E_g)^{1/2}}{E} [f_c(E_2) - f_v(E_1)] \, \text{cm}^{-1} \quad R_{sp}(E) = 1.15 \times 10^{29} E^{1/2} \left( E - E_g \right)^{1/2} f_c(E_2)[1 - f_v(E_1)] \, \text{s}^{-1} \text{cm}^{-3} \text{(eV)}^{-1}$$

Assuming the following parameters for the laser: $L = 400 \, \mu m$, $R_1 = R_2 = 0.9$, $\alpha = 10^3 \, \text{cm}^{-1}$, $\Gamma = 0.95$, $\eta_i = 0.9$, $\eta_{\text{inj}} = 1$. Along your calculation, verify that you obtain the following results:
Exercise: Efficiencies of an InP Laser

An InP Fabry-Perot laser emits at wavelength $\lambda \approx 920$ nm. It has an injection efficiency $\eta_{\text{inj}} = 90\%$ and an internal quantum efficiency $\eta_i = 95\%$. The voltage applied to the device is 2.5V. The reflectivity of both cavity ends are $R_1 = 100\%$ and $R_2 = 70\%$. The loss coefficient of the laser medium is $\alpha = 1$ cm$^{-1}$. Its threshold current is characterized to be $I_{\text{th}} = 1$ mA.

(a) The semiconductor laser has a cavity length $L = 400$ µm. Assume the refractive index $n = 3.3$. What should be the exact emission wavelength? At which longitudinal mode does lasing occur?

(b) Calculate the photon extraction efficiency, external quantum efficiency, and slope efficiency of the device.

(c) If the laser is operated at an injection level twice the threshold, find its power conversion efficiency and output power.
Transient phenomena occur because of the time required for the electron and photon populations to come into equilibrium. As the photon population builds up rapidly, the carrier density is depleted until it falls below transparency condition. → Photon population decreases. → Carrier population starts to build up again, this time from a higher initial value, and so does the photon population.

![Graph showing electron and photon density over time](image)

**Figure 7.32** Calculated transient response of the electron and photon densities in a InP-based lattice-matched In$_{0.53}$Ga$_{0.47}$As QW laser showing the relaxation oscillations. The switching is from 0 to 1000 A/cm$^2$ (courtesy of J. Singh, University of Michigan).
Frequency Response under Small-signal Modulation

As the initial oscillations cease, the situation becomes periodic small-signal modulation of a laser.

Complex response function:

\[ r(\Omega) = r | e^{i\phi} = \frac{m \gamma_c \gamma_n}{\Omega^2 - \Omega_r^2 + i\Omega \gamma_r} \]

Modulation power spectrum:

\[ R(f) = |r(f)|^2 = \frac{m^2 \gamma_c^2 \gamma_n^2}{16\pi^4 \left( f^2 - f_r^2 \right)^2 + 4\pi^2 f^2 \gamma_r^2} \]

Resonance peak:

\[ f_{pk} = \left( f_r^2 - \frac{\gamma_r^2}{8\pi^2} \right)^{1/2} \]

3-dB modulation bandwidth:

\[ f_{3dB} = \left( 1 + \sqrt{2} \right)^{1/2} \left( f_r^2 - \frac{\gamma_r^2}{8\sqrt{2}\pi^2} \right)^{1/2} \]

**Figure 7.33** Relative modulation response of a 6 × 130 µm² In₀.₃₅Ga₀.₆₅As/GaAs MQW laser at various bias currents. The device exhibited a -3dB bandwidth of 37 GHz for a bias current of 160 mA (from S. Weisser et al., LEOS ’95 Conference Proceedings, Vol. 1, p. 92 ©1995, IEEE).
Exercise: Modulation Characteristics

A GaAs QW VCSEL has the following parameters: Emission wavelength = 850 nm, refractive index $n = 3.52$, gain overlap factor $\Gamma = 0.2$, threshold gain coefficient $g_{th} = 8.16 \times 10^4 \text{ m}^{-1}$, excess carrier spontaneous lifetime $\tau_s = 3.02 \text{ ns}$, gain cross-section $\sigma = 2.2 \times 10^{-19} \text{ m}^2$.

(a) Find the values of spontaneous carrier relaxation rate $\gamma_s$ and cavity decay rate $\gamma_c$. What is the photon lifetime $\tau_c$?

(b) If the laser output power $P_{out} = 60.6 \mu\text{W}$, the mode volume $V_{mode} = 4.74 \times 10^{-18} \text{ m}^3$, the emitted and photon extraction efficiency $\eta_t = 89\%$. Find the intracavity photon density $S_0$.

(c) Find the values of differential gain parameter $g_n$. Assume the nonlinear gain parameter $g_p = -g_n$, find the values of differential carrier relaxation rate $\gamma_n$ and nonlinear carrier relaxation rate $\gamma_p$.

(d) Find the values of relaxation resonance frequency $f_r$ and total carrier relaxation rate $\gamma_r$.

(e) Find the resonance peak of the modulation spectrum $f_{pk}$. What is the 3-dB modulation bandwidth $f_{3dB}$?
Heterojunction Lasers

$I_{th}$ for homostructure laser diode extremely high
$\rightarrow$ Not practical for room temperature operation

Heterostructure laser: Enhance *carrier confinement* and *photon confinement*

- **Electrodes**: 
  - $n$-GaAs (Substrate)
  - $p$-GaAs (Contacting layer)
  - $p$-$\text{Al}_x\text{Ga}_{1-x}$As (Confining layer)
  - $n$-$\text{Al}_x\text{Ga}_{1-x}$As (Confining layer)
  - $n$-GaAs (Active layer)

- **Active region**: $J > J_{th}$

- **Current paths**: 1, 2, 3

- **Elliptical laser beam**

- **Cleaved reflecting surface**

- **Substrate**

- **Stripe electrode**

- **Oxide insulator**

- **Refraction index**

- ** Photon density**

- **Active region where** $J > J_{th}$. 

**Graphical Elements**:
- Rectangular diagram showing heterojunction layers.
- Energy band diagram illustrating carrier and photon confinement.
- Cross-sectional view of the laser structure with labels for layers and current paths.
DBR Laser and DFB Laser

Output spectrum of a typical Fabry-Perot (F-P) laser

\[ \frac{2L}{\lambda} = q \]

→ Many wavelengths are possible, as long as they are within the gain spectrum

How do we obtain single-frequency semiconductor lasers?

**Distributed Bragg reflector (DBR) laser**

**Distributed feedback (DFB) laser**

\[ v_m \approx v_B \pm (m + \mu) \frac{c}{2n_B l} \]
Typical Grating Coupler Structure and Coupled-Mode Theory

Coherent coupling between forward- and backward-propagating waves results in selection of longitudinal modes.

\[ \delta = \beta_B - \beta(\omega) \]

\[ R = \sinh^2 \left( \kappa |L\sqrt{1 - |\delta|/\kappa|^2} \right) / \cosh^2 \left( \kappa |L\sqrt{1 - |\delta|/\kappa|^2} \right) - |\delta|/\kappa|^2 \]
Exercise: DBR Laser

A DBR laser has gain section of length $l = 400 \mu m$ and two identical DBRs as end mirrors, each of length $l_{DBR} = 150 \mu m$. The grating period of the DBR is $\Lambda = 225 \, nm$. The effective indices for the laser modes are $n_{\beta} = N_{\beta} = 3.45$. The DBR coupling coefficient is $|\kappa| = 50 \, cm^{-1}$. The gain spectrum peaks $\sim 1550 \, nm$.

(a) Find the Bragg wavelength and frequency near the gain peak.
(b) Find the peak reflectivity and the bandwidth of the two DBRs.
(c) Find the effective phase length of the DBRs and that of the DBR laser to determine the longitudinal mode spacing of the laser.
(d) Assume the gain bandwidth is much broader than the DBR frequency bandwidth, how many longitudinal modes can exist?
(e) If the laser is pumped right at the threshold, only one mode can oscillate. What’s its wavelength? Calculate the DBR reflectivity at this lasing wavelength.
Vertical Cavity Surface Emitting Laser (VCSEL)

Dielectric mirrors → Distributed Bragg reflector structures

A 1st-order square grating of a 50% duty factor has the largest coupling coefficient

$$| \kappa | = \frac{2 \Delta n}{\lambda}$$

$$\Lambda = \frac{\lambda_B}{2 \overline{n}}$$