Lecture 8

Material and Homework

Read:

Chapter 5 Section 5.4, 5.6 Yariv and Yeh

Chapter 6 Sections 6.1-6.5 Yariv and Yeh

Chapter 3 Section 3.0-3.2 Yariv and Yeh

Chapter 15 Yariv and Yeh

Appendices 1 and 2 in Coldren (on reserve)

Homework #3

Due Tuesday, May 2, 2006

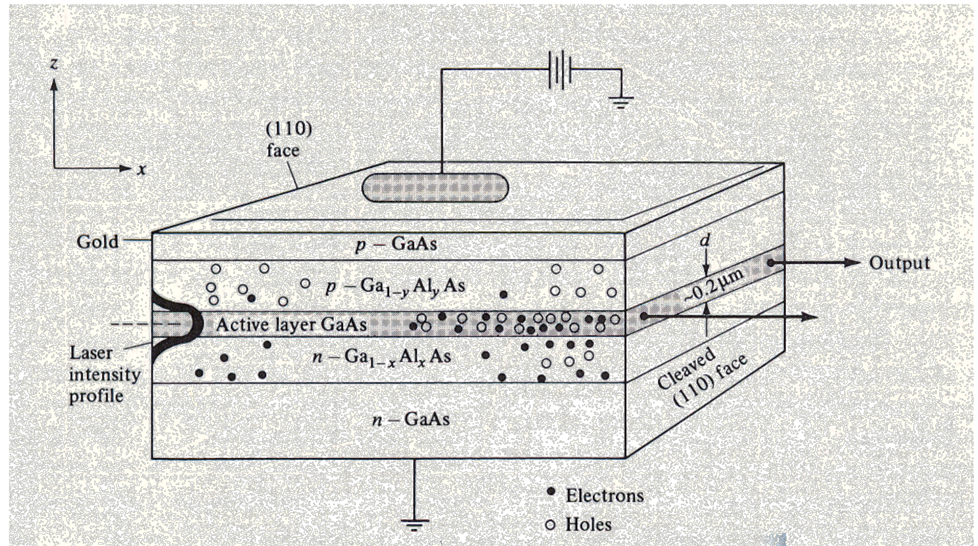
a. Derive equation 5.4-1 in Yariv starting with equation 5.3-8
b. Problem 5.1 Yariv
c. Problem 5.6 Yariv

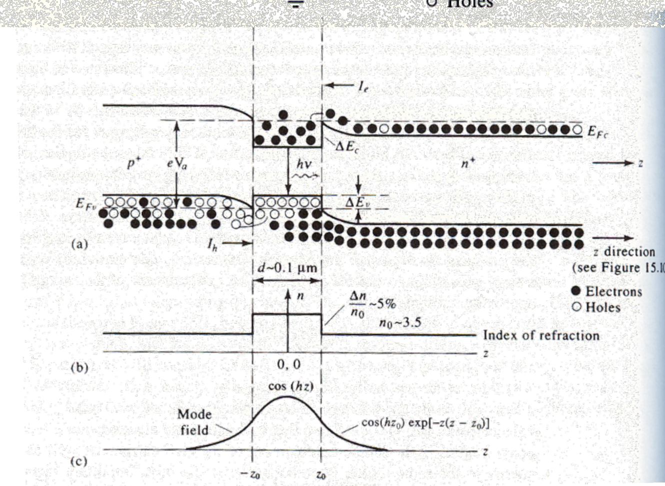
GaAs/GaAlAs and GaInAsP Lasers

- GaAs/ $Ga_{1-x}Al_xAs$ Lasers
  - Active region (gain) is either GaAs or $Ga_{1-x}Al_xAs$.
  - AlAs has a larger bandgap than GaAs
    - Therefore $Ga_{1-x}Al_xAs$ has a bandgap in between
  - X indicates fraction of Ga atoms in GaAs
  - Light frequency emission depends on active region x and its doping
    - $0.75\ \mu m < \lambda < 0.88\ \mu m$
- $Ga_{1-x}In_xAl_{1-y}P_y$ Lasers
  - Active region is $Ga_{1-x}In_xAl_{1-y}P_y$
  - Light frequency emission depends on active region x and y and its doping
    - $1.1\ \mu m < \lambda < 1.6\ \mu m$

GaAs/$Ga_{1-x}Al_xAs$ Double Heterostructure Lasers

- Three layered dielectric waveguide
  - Thin active layer undoped
  - Cladding GaAlAs layers heavily dope p and n
  - Index contrast approximately given by
    - $n_{GaAs} - n_{Ga_{1-x}Al_xAs} \cong 0.62x$
- Under positive bias
  - e^- injected into active region from n-side and h^+ from p-side
  - Injected electrons prevented from diffusing out of active region due to ΔE_c. Injected holes prevented from diffusing out of active region due to ΔE_v.
    - $\Delta E_c \cong 0.6E_g$; $\Delta E_v \cong 0.4E_g$
- Double confinement of injected carriers and optical mode to the same active region.





Yariv and Yeh, ***Photonics***

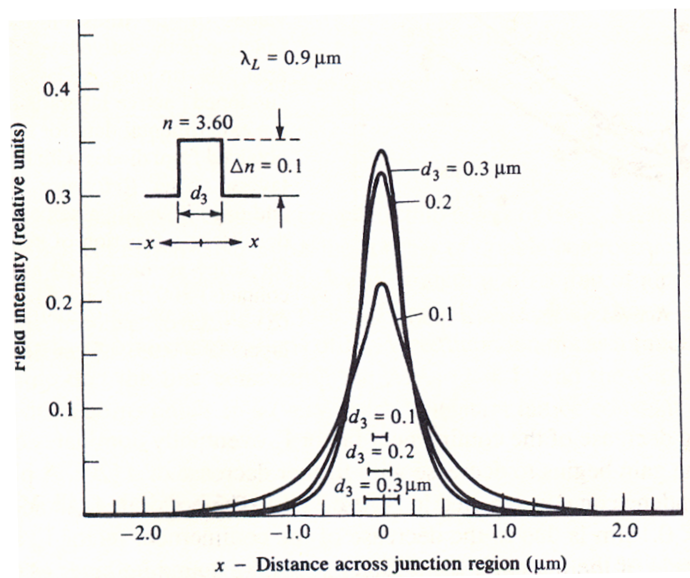
Modal Gain

- When the gain coefficient γ is constant over active region width, the ***modal gain*** can be defined as

$$g = \gamma\Gamma_a - \alpha_n\Gamma_n - \alpha_p\Gamma_p$$

$$\Gamma_a = \frac{\int_{-d/2}^{d/2} |E|^2\,dz}{\int_{-\infty}^{\infty} |E|^2\,dz};\Gamma_n = \frac{\int_{-\infty}^{-d/2} |E|^2\,dz}{\int_{-\infty}^{\infty} |E|^2\,dz};\Gamma_p = \frac{\int_{d/2}^{\infty} |E|^2\,dz}{\int_{-\infty}^{\infty} |E|^2\,dz}$$

- α_n is the loss in un-pumped n-type GaAlAs and α_p loss in un-pumped p-type GaAlAs. γ is gain in pumped active layer. Γ_a, Γ_n, Γ_p are the fraction of optical mode power in the active region, n-type and p-type cladding regions respectively.
- Varying d changes the mode shape and relative confinement to the active and surrounding cladding regions as shown by example on the right.
- The mode shape we are talking about here is the gain guided (vertical) mode shape. The mode lateral confinement will be discussed a little later in the lecture.



Yariv and Yeh, Photonics

Threshold Current Density

- As d decreases, Γ_a decreases, and more mode power propagates outside the active region and does not receiver gain and can be attenuated.
- Threshold gain condition can be written as

$$\gamma\Gamma_a = \alpha_n\Gamma_n + \alpha_p\Gamma_p - \frac{1}{L}\ln R + \alpha_s$$

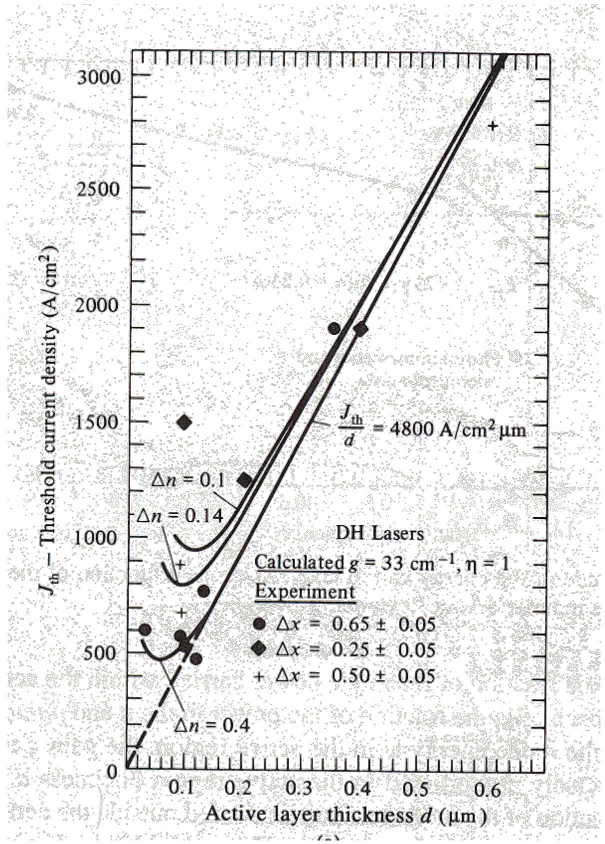
- Given losses, R and confinement factors, we can calculate the gain γ required for threshold.
- Under steady state, the carrier injection rate equals the electron-hole recombination rate, and the electron hole recombination rate can be calculated for the required γ

$$\frac{J}{q} = \frac{Nd}{\tau}$$

$$\frac{J}{d} = \frac{Nq}{\tau}$$

$$\frac{J_{th}}{d} = \frac{N_{th}q}{\tau}$$

- Threshold current density (J_{th}/d) is plotted on the right as a function of active layer thickness for a broad area (low lateral confinement) laser



Yariv and Yeh, Photonics

Power Output

- As the injected current increases beyond threshold, the laser oscillation intensity increases and the stimulated emission dominates the carrier lifetime to the point where the inversion is clamped at its threshold value
- For η_i defined as the probability that an injected carrier recombines radiatively in the active region, the power emitted via stimulated emission is (we derived this previously for steady state)

$$P_e = \frac{(I - I_{th})\eta_i}{q} h\nu$$

- The total stimulated radiation is either absorbed in the cavity or eventually escapes out of the laser cavity as output power.

$$P_o = \frac{(I - I_{th})\eta_i}{q} h\nu \frac{\left(\frac{1}{L}\right)\ln\left(\frac{1}{R}\right)}{\alpha + \left(\frac{1}{L}\right)\ln\left(\frac{1}{R}\right)}$$

Differential Quantum Efficiency

- The ratio of the photon output rate resulting from a given input carrier injection rate is the external differential quantum efficiency η_{ex}

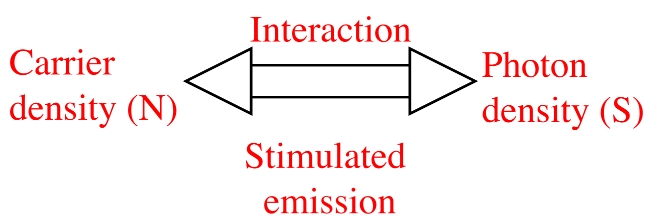
$$\eta_{ex} = \frac{d\left(P_O / h\nu\right)}{d\left[(I - I_{th}) / q\right]}$$

- And the overall laser efficiency is

$$\eta_{ex} = \frac{P_O}{IV_{appl}} = \eta_i \frac{I - I_{th}}{I} \frac{h\nu}{qV_{appl}} \frac{\ln\left(\frac{1}{R}\right)}{\alpha L + \ln\left(\frac{1}{R}\right)}$$

Small Signal Modulation

- Relaxation oscillation: Is due to an interaction between the carrier and photon density



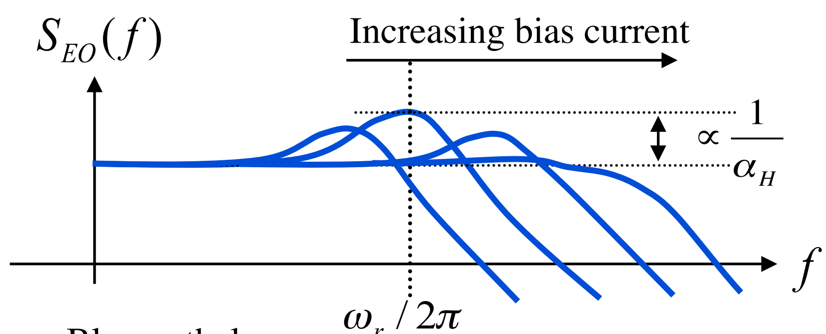
$$\frac{dN}{dt} = \frac{I}{qV} - \frac{N}{\tau_n} - G(N)\cdot(1-\varepsilon\cdot S)\cdot S$$

$$\frac{dS}{dt} = \Gamma_a \cdot G(N)\cdot(1-\varepsilon\cdot S)\cdot S - \frac{S}{\tau_p} + \frac{\Gamma_a \beta_{sp} N}{\tau_n}$$

- Define the relaxation frequency

$$\omega_r = \sqrt{\omega_n^2 - \alpha^2} \propto 2\pi\sqrt{\frac{\frac{\partial G}{\partial N}P}{\tau_p}}$$

- Where :
  - α = damping constant. Increases with increasing photon density in steady state.
  - ω_r increases with increasing bias current.



- Why do most transmitters bias the off level of the laser close to threshold instead of zero bias?

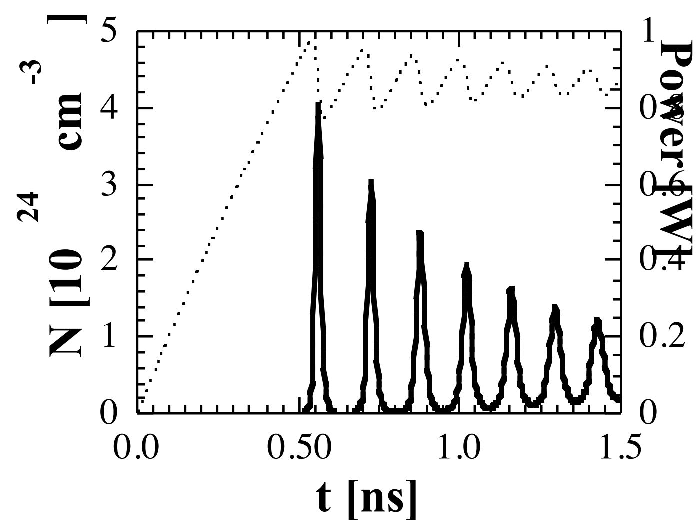
Large Signal Modulation
Step Response

Turn-on delay:

$$\tau_d = \tau_n \ln\left(\frac{I - I_b}{I - I_{th}}\right)$$

Oscillation frequency:

$$f_r = \sqrt{\frac{1 + \Gamma v_g a N_{tr} \tau_p}{\tau_p \tau_n}\left(\frac{I - I_{th}}{I_{th}}\right)}$$



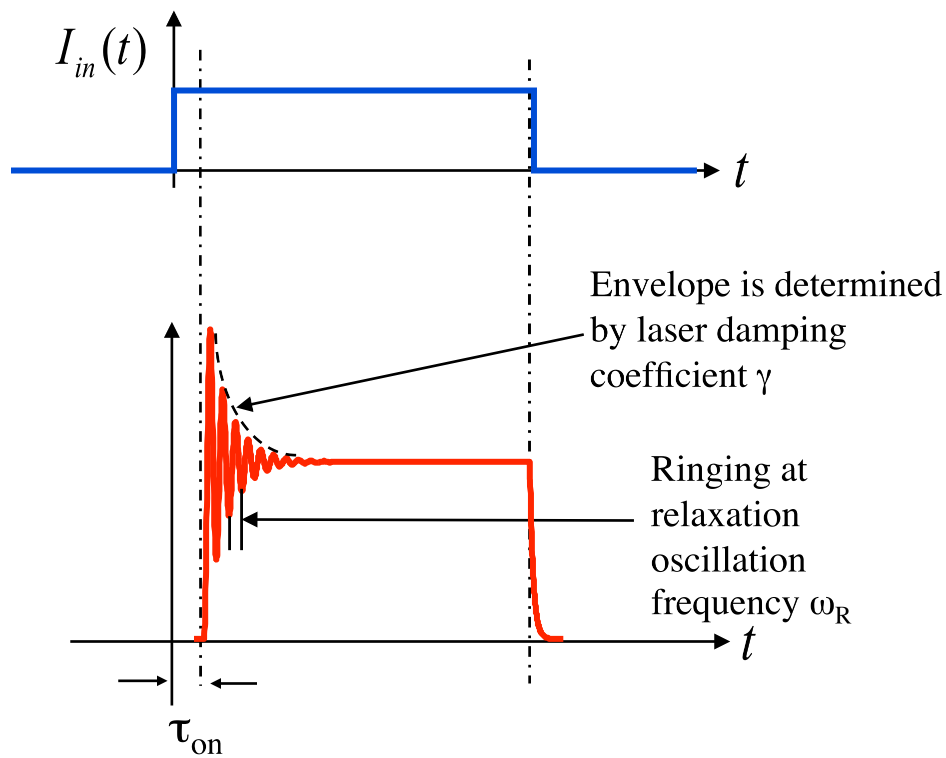
Large Signal (Digital) Modulation

- Pulse response of a directly-driven semiconductor laser
  - Laser turn-on delay τ_D is determined by drive circuit/laser combination.
    - Determined by the "zero" current level (below or above threshold)

$$\tau_{on} = \frac{\sqrt{2}}{2\pi f_r}\left[\ln \frac{P_{on}}{P_{off}}\right]$$

  - Want α to dampen out relaxation oscillation well within the bit interval.
    - Choose I_{bias} to set frequency and magnitude of relaxation oscillation relative to bit period

$$\gamma = \frac{\Gamma \varepsilon P_0}{V \eta h \nu}$$



Digital Modulation

- What does NRZ mean?
  What does RZ mean?
  What is an eye diagram?