Semiconductor Lasers

ECE 162C

Lecture #8

Prof. John Bowers

Read Kasip, Chapters 3,4

Midterm: May 5. Chapters 1-4

•ECE 162C: PROBLEM SET #4
DUE FRIDAY, MAY 2, 2004, 4 pm
(No late submissions because the solution will be emailed out).

•PROBLEM:

Consider a 1.3 μm buried heterostructure InGaAsP /InP bulk laser 400 μm in length with confinement factor Γ=.2, internal quantum efficiency of 80% and internal loss of 10 cm^{-1}, cleaved facets, 0.2 μm thick active region, 2 μm wide waveguide, 1ns lifetime, linear gain dependence on carrier density with a differential gain 2×10^{16} cm^2 and transparency carrier density of 1×10^{18} cm^{-3}. Assume the index of the active region is 3.5 and the index of the InP cladding is 3.17, and the group index is 3.6. Assume the mirror reflectivity is 0.3.

- Draw the transverse conduction band and valence band diagrams under zero bias and forward bias.
- Sketch the electron and hole carrier densities under zero and forward bias.
- Plot the peak gain versus carrier density.
- What is the mirror loss?
- What is the threshold modal gain?
- What is the threshold current?
- What is the differential quantum efficiency?
- What is the axial mode spacing?
- Calculate the width for a single transverse mode. Is the laser single transverse mode?
- Calculate the width for a single lateral mode. Is the laser single lateral mode? (Use the effective index method).

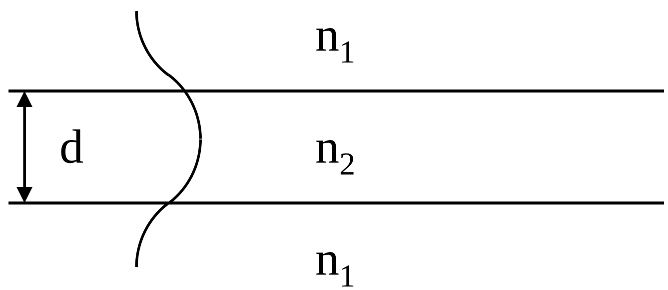
Symmetric 3 Layer Guide

- Solve wave equation
  - Sinusoidal solutions and exponential solution
  - Match boundary conditions at interface
  - Apply boundary condition at infinity

$$k_x^2 = k_0^2 n_2^2 - \beta^2$$

$$\gamma^2 = \beta^2 - k_0^2 n_1^2$$

$$k_x \tan \frac{k_x d}{2} = \gamma$$



Symmetric 3 Layer Guide

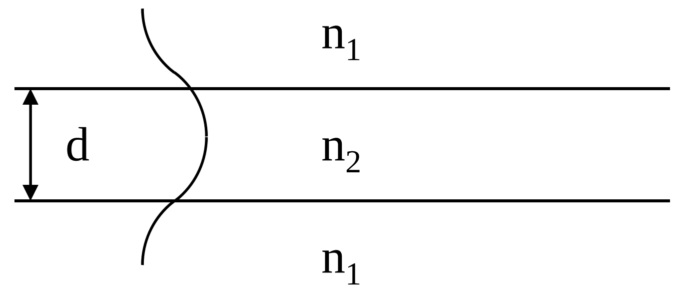
- Plot graphically

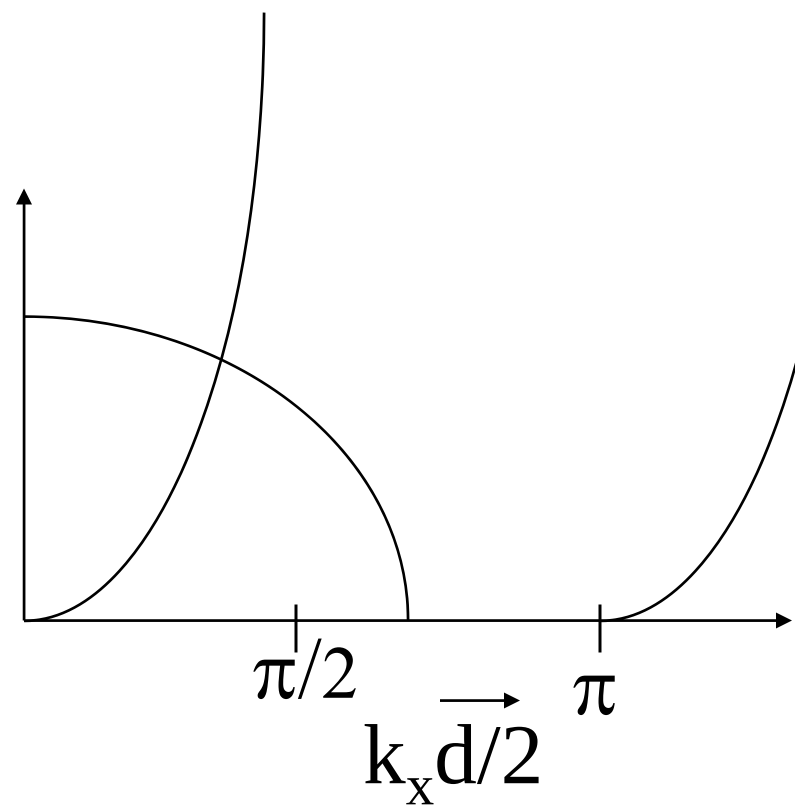
$$k_x^2 = k_0^2 n_2^2 - \beta^2$$

$$\gamma^2 = \beta^2 - k_0^2 n_1^2$$

$$k_x \tan\frac{k_x d}{2} = \gamma$$

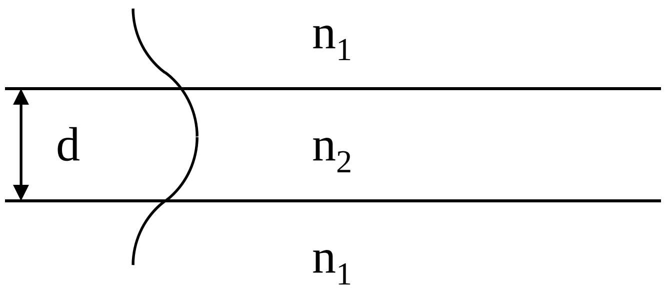
$$k_x \tan\frac{k_x d}{2} = \sqrt{k_0^2(n_2^2 - n_1^2) - k_x^2}$$





Symmetric 3 Layer Guide

- Asymmetric solutions



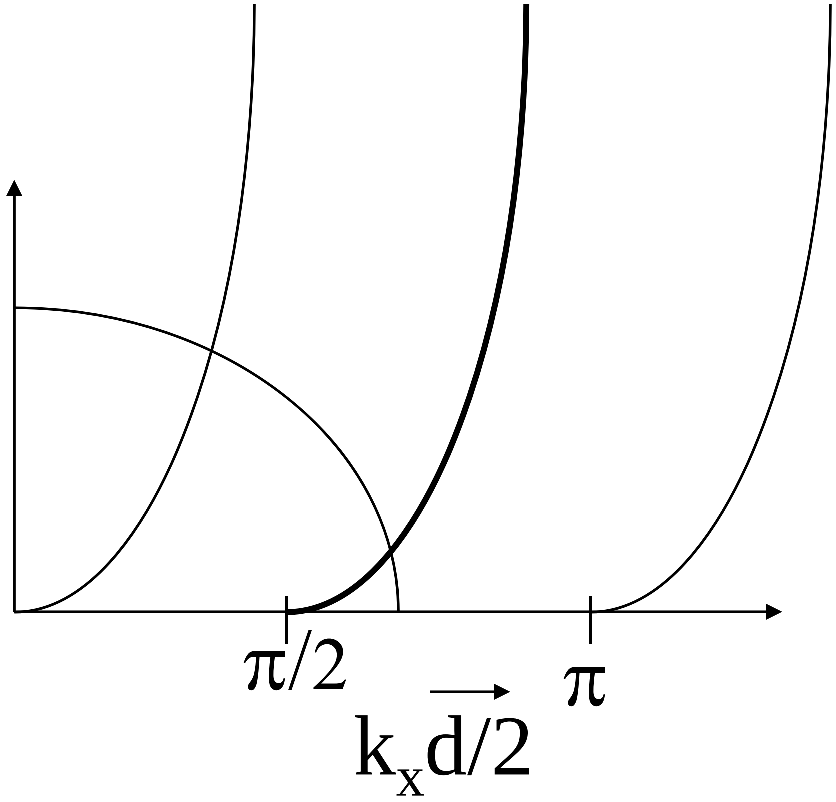
$$k_x^2 = k_0^2 n_2^2 - \beta^2$$

$$\gamma^2 = \beta^2 - k_0^2 n_1^2$$

$$k_x \cot \frac{k_x d}{2} = -\gamma$$

$$k_x \cot \frac{k_x d}{2} = \sqrt{k_0^2 (n_2^2 - n_1^2) - k_x^2}$$

$$d < \frac{\pi}{k_0^2 \sqrt{(n_2^2 - n_1^2)}}$$



Single mode condition

Effective Index Method

1. Do transverse calculation (y)
   - Neglect variation in lateral direction(x)
   - Calculate effective index n in each region
2. Do lateral calculation
   1. Neglect variation in transverse direction(y)
   2. Calculate effective index of mode.

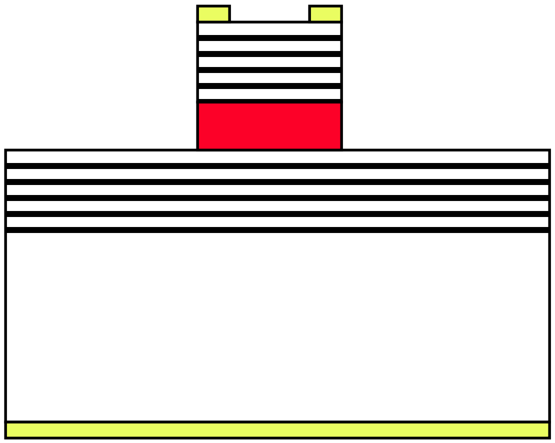
This method is reasonably accurate when

1. The width is much larger than the thickness (lateral>transverse)
2. The lateral confinement is relatively weak.

Semiconductor Lasers

- In-plane lasers
  - CD lasers, most telecom lasers
  - Simple, low cost die
  - divergence angle is large, coupling to fiber difficult
  - Requires cleaving for lasing

- Vertical Cavity Laser
  - Simple to make arrays
  - Single frequency (for small aperature)
  - Short gain section
  - Requires high reflectivity mirrors
  - Most datacom (850 nm transceivers)



Guiding

- Gain guided
  - simple
  - far field not stable, poor for fiber coupling
  - higher loss
- Index guided
  - smaller mode, lower threshold
  - stable modes (mode determined by index difference, not by carrier levels

Polarization

- Transverse electric (TE) or Transverse magnetic (TM) are possible.
- Most lasers are TE.
  – The difference in confinement factor (i.e. lower modal gain for TM) and the difference in reflectivity tend to select TE operation.

Modes

- Transverse (vertical)
  - Virtually all lasers have single transverse mode; simple to obtain, only requires ability to grow thin layers (0.2 micron—not all that thin)
- Lateral modes
  - Most laser waveguides sustain multiple lateral modes (1 to 2 micron is above the single mode limit)
  - Lasers of width below 1.5 micron tend to lase single mode because the lowest order mode has the lowest threshold; higher order modes don't reach threshold
  - Lasers of width above 2 micron tend to have multiple lateral modes; difficult to couple to single mode fiber efficiently
- Longitudinal modes
  - Fabry Perot lasers tend to lase in 5-10 modes
  - Something must be done to select 1 mode

Single Mode Lasers

- At least 3 cm^{-1} of gain difference between the dominant mode and other modes is required.
  - Less gain difference: The laser may lase cw in a single mode, but lases in multiple modes when modulated.
  - More gain difference necessary to achieve 40 dB sidemode suppression under 100% modulation.

Threshold Carrier Density

Threshold gain

$$\Gamma g_{th} = \alpha_i + \alpha_m$$

Approximate gain as linear (good for bulk regions; ln dependence better for quantum wells)

Ntr is the transparency value.

dg/dN is the differential gain

$$g_{th} = \frac{dg}{dN}(N_{th} - N_{tr})$$

Note that the carrier density is clamped at the threshold value; otherwise, the photon density would increase to infinity.l

Rate Equations

$$\frac{dS}{dt} = \frac{\Gamma v_g a\left(N - N_{tr}\right)}{1+\varepsilon S} S - \frac{S}{\tau_p} + \frac{\beta \Gamma N}{\tau_n}$$

$$\frac{dN}{dt} = \eta_i \frac{I}{qV} - \frac{v_g a(N - N_{tr})}{1+\varepsilon S} S - \frac{N}{\tau_n}$$

- To get cw threshold, assume cw behavior (dN/dt=0) and use electron rate equation

$$\frac{dN}{dt} = \eta_i \frac{I}{qV} - \frac{v_g a(N - N_{tr})}{1+\varepsilon S} S - \frac{N}{\tau_n}$$

$$\eta_i \frac{I_{th}}{qV} = \frac{N_{th}}{\tau_n}$$

$$I_{th} = \frac{qVN_{th}}{\eta_i \tau_n}$$

Threshold Current

$$I_{th} = \frac{qVN_{th}}{\eta_i \tau_n}$$

$$I_{th} = \frac{qV}{\eta_i \tau_n}\left(N_{tr} + \frac{\alpha_i + \alpha_m}{\Gamma dg / dN}\right)$$

L-I Curve

- Use the electron rate equation (neglect εS)

$$\frac{dN}{dt} = \eta_i \frac{I}{qV} - \frac{v_g a(N - N_{tr})}{1 + \varepsilon S} S - \frac{N}{\tau_n}$$

$$0 = \eta_i \frac{I}{qV} - v_g g_{th} S - \frac{N}{\tau_n}$$

$$v_g g_{th} S = \eta_i \frac{I}{qV} - \frac{N}{\tau_n}$$

$$S = \frac{\eta_i (I - I_{th})}{qVv_g g_{th}}$$

L-I Curve

- Convert from photon density to output power

The number of photons in the cavity is SV_p

The energy of photons in the cavity is $h\nu SV_p$

The output power is

$$P = v_g \alpha_m h\nu SV_p$$

$$S = \frac{\eta_i (I - I_{th})}{qVv_g g_{th}}$$

$$P = \frac{v_g \alpha_m h\nu V_p \eta_i (I - I_{th})}{qVv_g g_{th}}$$

$$P = \frac{\eta_i \alpha_m}{\alpha_i + \alpha_m} \frac{h\nu}{q} (I - I_{th})$$

External differential quantum efficiency

$$P = \frac{\eta_i \alpha_m}{\alpha_i + \alpha_m} \frac{h\nu}{q} (I - I_{th})$$

The differential quantum efficiency is (%)

$$\eta_d = \frac{\eta_i \alpha_m}{\alpha_i + \alpha_m}$$

The slope efficiency is (W/A)

$$R_l = \frac{\eta_i \alpha_m}{\alpha_i + \alpha_m} \frac{h\nu}{q}$$

$$\frac{dP}{dI} = R_l$$

Laser Requirements

- Confinement of the optical mode
  - Transverse
  - Lateral (rib, strip, gain guided)
  - Longitudinal (cleaved facets, rings, DFB, DBR,…)
- Confinement of carriers
  - Heterojunction, etched, no confinement (implanted, diffused,…)
- Confinement of current
  - Oxide
  - Homojunction
  - PN junction
  - Semi-insulating

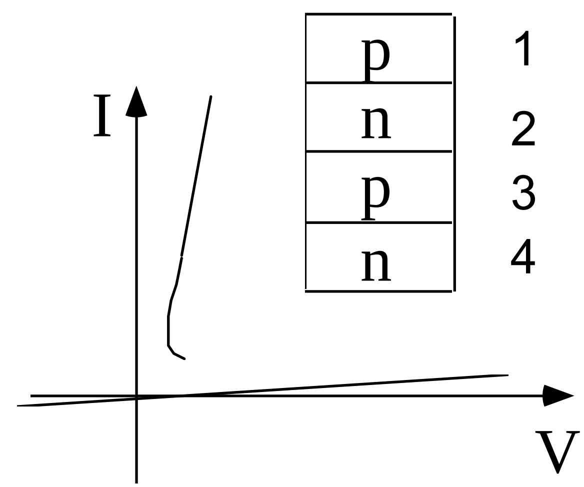
Laser Structure
Current Confinement

- Dielectric layers, e.g. SiO_2, SiN_x, polyimide or oxidized AlGaAs
  - Very low capacitance
  - Possible reliability problem
  - Poor thermal characteristics
- Reverse biased p-n junctions
  - Good high power and high T capability
  - Large depletion capacitance
- Larger bandgap homojunctions
  - Simple fabrication
  - Leakage current and diffusion capacitance are high
- Semi-insulating semiconductor regions
  - Low capacitance and good high T and high power performance
  - Growth of high quality semi-insulating layers not trivial

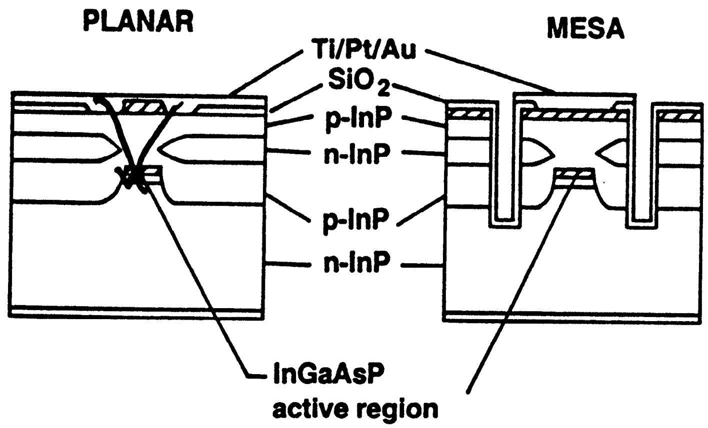
Parasitic Thyristor

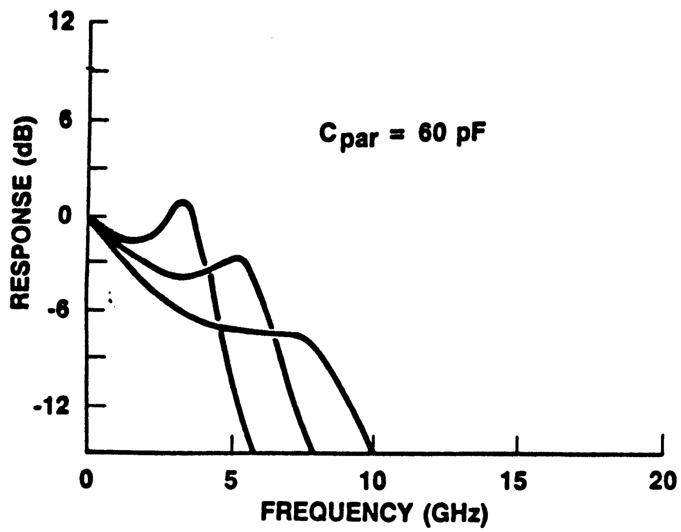
Problem for devices where current confinement is obtained with reverse biased p-n junctions.

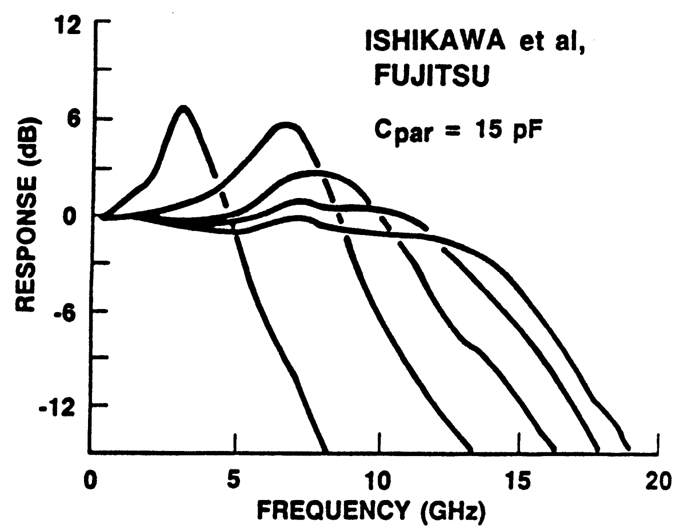
- At low bias junction 2-3 is reverse biased, preventing current flow
- When bias is increased we get hole injection from 3->1



Laser Structure : High Speed Planar Laser



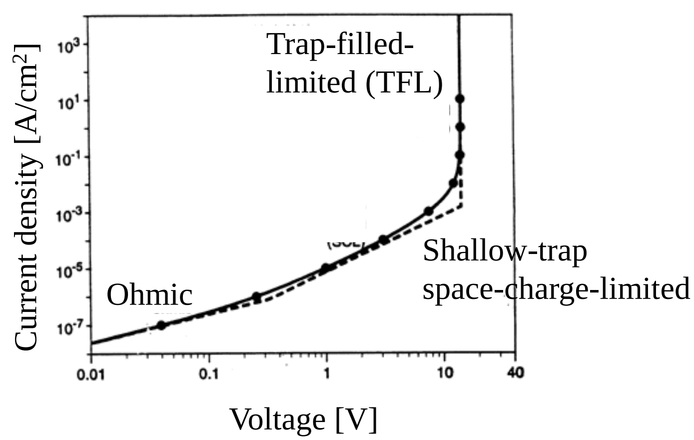




Semi-Insulating Fe:InP

- Fe is a deep level acceptor in InP, making the material highly resistive to electron current. However, if the Fe-doped layer is placed between p- and n- material, holes are injected and can recombine with electrons, i.e. current is flowing.
- Use n-SI-n structure
  - avoids double injection
- At high bias levels all traps are filled.

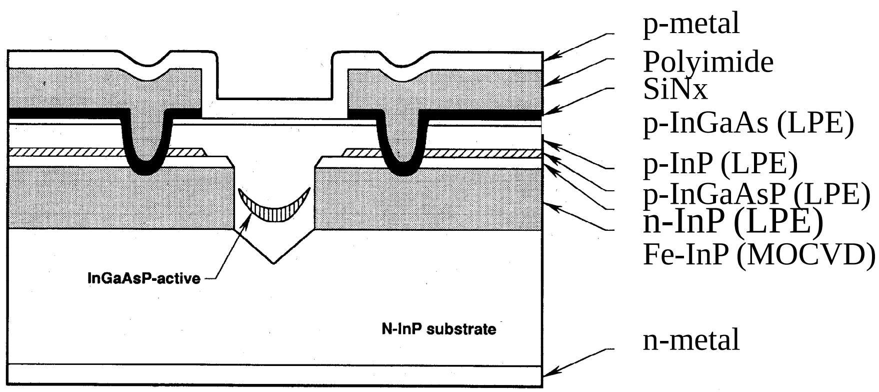
$$V_{TFL} = \frac{eN_t L^2}{2\varepsilon}$$



Laser Structures

Semi-insulating buried crescent laser

Current confinement achieved with Fe-doped semi-insulating layer



R.-T. Huang et al., Photon. Technol. Lett., vol. 4, no. 4, 293 (1992)