Lecture 11 -Optical Sources and Transmitters

Table 1 - MSA Standards Overview

[illegible]	Synopsis
[illegible] rs	
[illegible]	"Small Form Factor Pluggable" popular mainstream pluggable for data rates to 2.5 Gb/s, up to 4 Gb/s Fiber Channel SFP+ being promoted for 10 Gb/s QSFP for 4 channel implementations DWDM versions available for Metro telecom systems www.sffcommittee.org
XFP	"10G Small Form Factor Pluggable" 10GbEthernet, OC192, (10G FC anticipated) Available in non-WDM, CWDM and DWDM versions Available to 80 km reach www.xfpmsa.org
10 Gbit Ethernet Transponders	
Xenpak	XAUI electrical interface Hot pluggable Large legacy market www.xenpak.org
Xpak / X2	Functionally equivalent to Xenpak, but XPAK and X2 are two rival mechanical designs in a smaller form factor. Designs do not require card cutout. Www.x2msa.org www.xpak.org
Other Selected Transponder Module MSAs	
300pin	Fixed pluggable transponder SFF (Small Form Factor) version more space efficient Large power dissipation budget allows advanced (high power) functions to be implemented 10GbE and OC192 Sonet/SDH Tunable Laser versions available. www.300pinmsa.org
Parallel Optics	
SNAP12, POP4, Quadlink	12 channel and 4 channel parallel optics modules for very short reach, ultra high bandwidth applications. www.snapoptics.org www.popoptics.org

Photon Energy and Bandgap

Energy of Photon

$$E_a - E_b = \hbar\omega = E_g + \frac{\hbar^2 k^2}{2m_c} + \frac{\hbar^2 k^2}{2m_v}$$

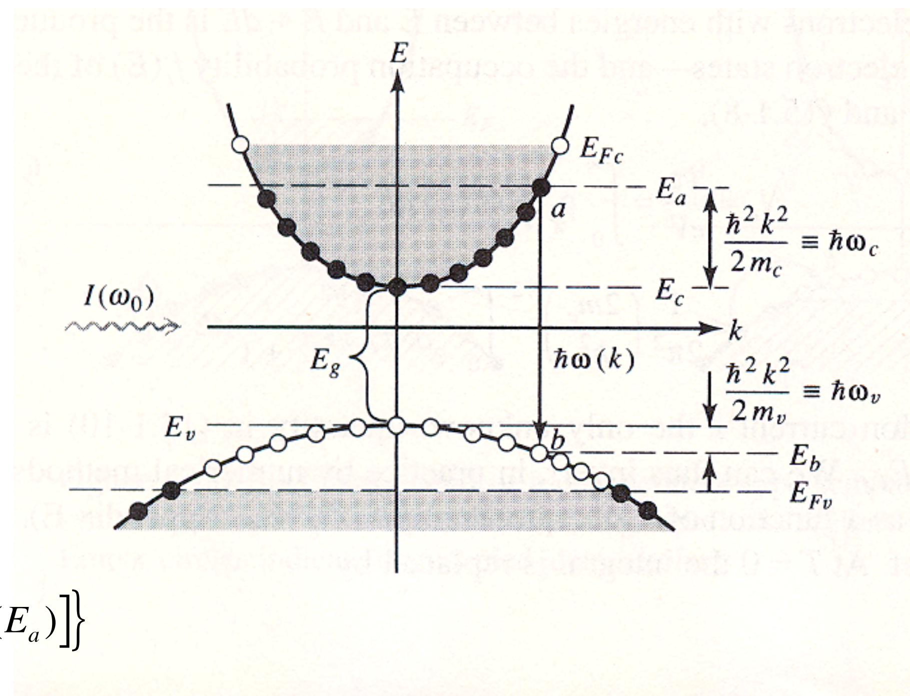
For an electron in upper state a and potential lower state b, the downward rate of transition is

$$R_{a\to b} \propto f_c(E_a)\left[1 - f_v\left(E_b\right)\right]$$

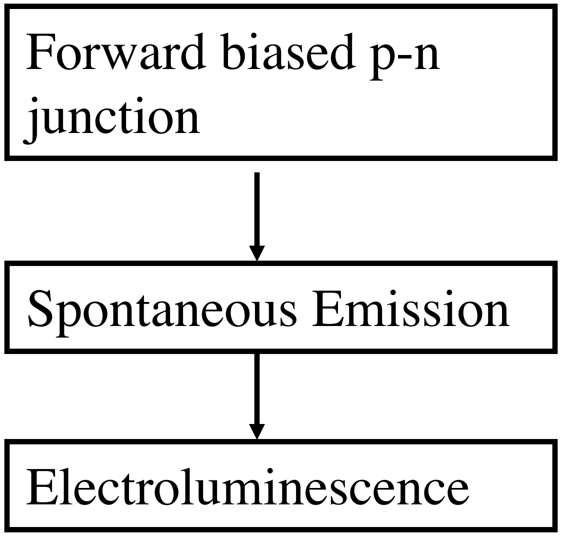
Effective inversion due to electrons and holes within dk

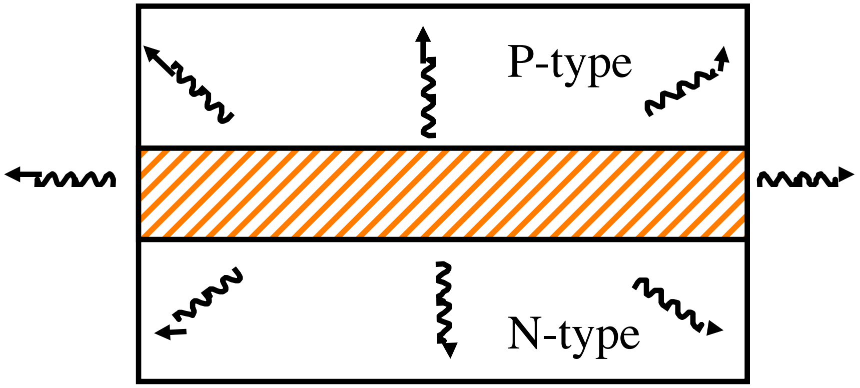
$$N_2 - N_1 \to \frac{\rho(k)dk}{V}\left\{f_c(E_a)\left[1 - f_v(E_b)\right] - f_v(E_b)\left[1 - f_c(E_a)\right]\right\}$$

$$= \frac{\rho(k)dk}{V}\left[f_c(E_a) - f_v(E_b)\right]$$



Light Emitting Diodes (LEDs)





•Light is emitted from forward biased junction in all directions

LED Optical Characteristics

- **Internal optical power** $$P_{int} = \left(\eta_{int} \frac{I}{q}\right)(\hbar\omega) = \left(\frac{\#\ photons}{\sec}\right)\left(\frac{energy}{photon}\right)$$

- **Output optical Power** $$P_{out} = \eta_{ext} P_{int} = \eta_{ext} \cdot \eta_{int} \frac{I}{q} \hbar\omega$$

  Internal quantum efficiency (η_{int})

  Output coupling efficiency (η_{ext})

- **Important: the output optical power is (to a first instance) proportional to the driving current:**

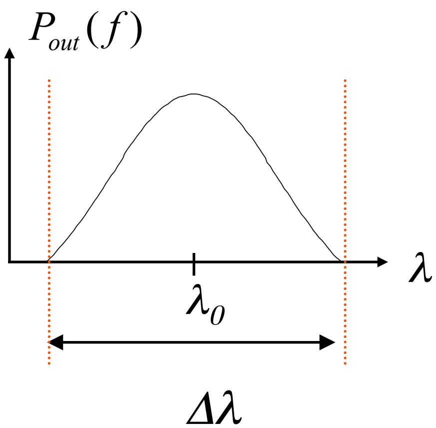
$$P_{out}(t) \cong k \cdot I(t)$$

LED Spectral Width

⇨ Full width half maximum spectral width: it is roughly given by:

$$\Delta\nu \approx 1.8 K_B T / h$$

$$\Delta\lambda \approx 1.8 K_B T \frac{\lambda^2}{ch}$$



⇨ Note that it is directly proportional to the device temperature T

Ex : **GaAs LEDs** (830 nm, 300 K) ⇒ ***Δλ≈ 30 nm***

InGaAsP LEDs (1310 nm, 300 K) ⇒ ***Δλ≈ 60 nm***

⇨ The output optical power (coupled in the output fiber pigtail) for most commercial LED is in the order of

–20 dBm to –10 dBm

LED Modulation Bandwidth

The average time it takes for an electron to arrive in the active region due to I_{bias} and for an electron to disappear from the active region due spontaneous recombination is called the carrier lifetime (τ_c)

LED Optical Bandwidth

$$f_{3dB,opt} = \frac{\sqrt{3}}{2\pi\tau_c}$$

LED Electrical Bandwidth

$$f_{3dB,ele} = \frac{1}{2\pi\tau_c}$$

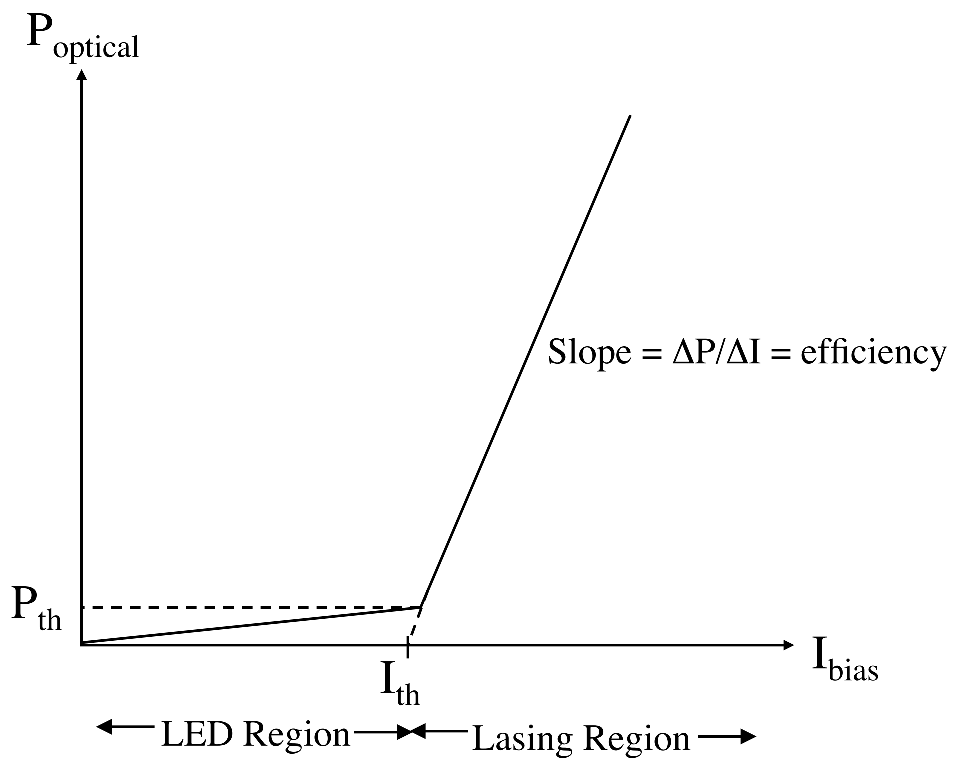
Example: τ_c is on the order of 1-5ns. Therefore the electrical bandwidth is on the order of

Important Laser Diode Parameters

- Light current curve:
  - Threshold current (typically I_{th}=1-20 mA)
  - Temperature dependence of threshold (T_0=100K)
  - Slope efficiency (typically R=0.2 mW/mA)
  - Quantum efficiency (fraction of input electrons that produce useful light) $\eta = R\, e/h\nu = R/(1.24 W/A/\lambda)$
- Near field and far field characteristics
  - Fiber coupling
- Spectra
  - Dispersion

Lasing Threshold

- Power-Current (P-I) Characteristics



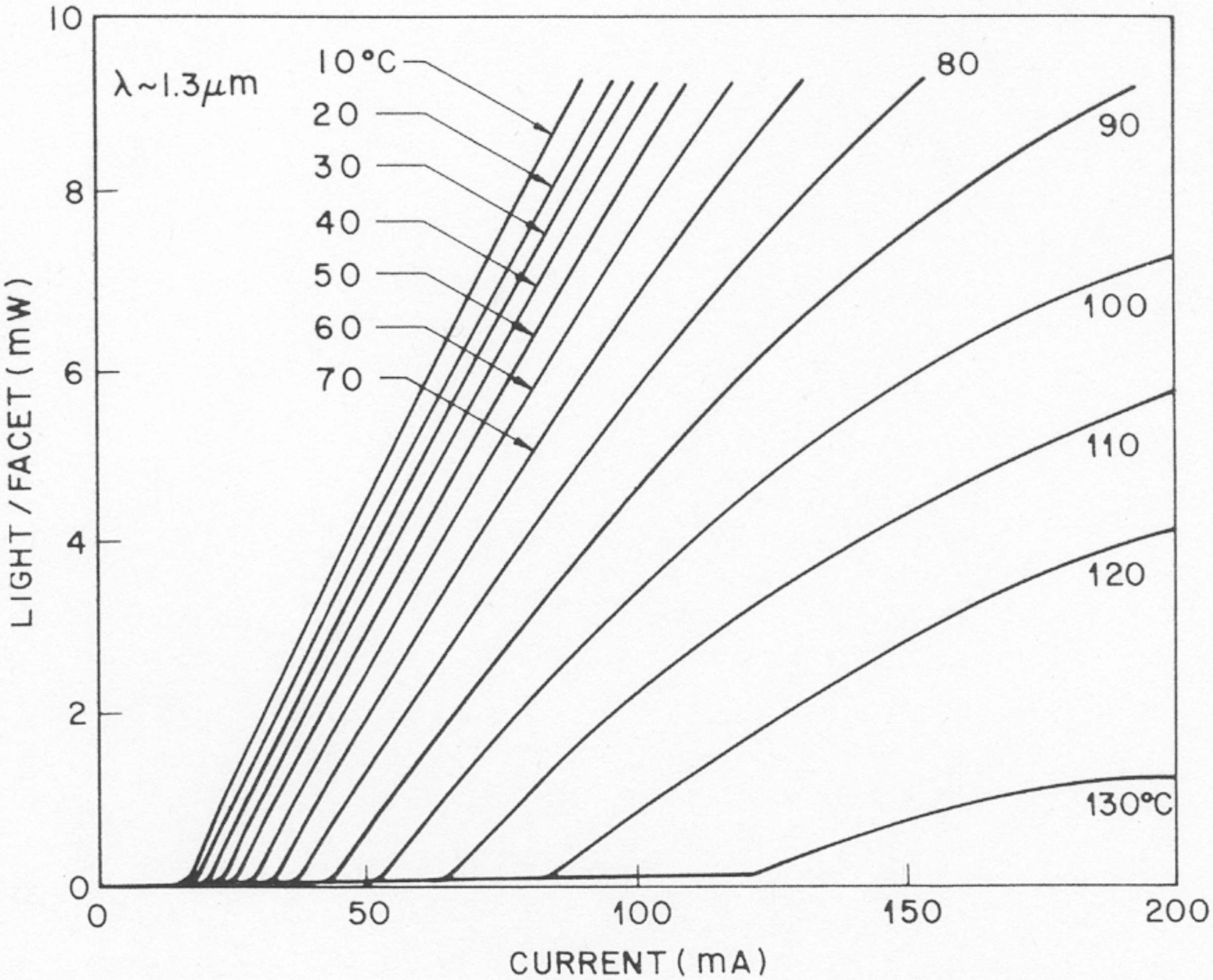


Fig. 5.25 L-I characteristics of a 1.3-μm InGaAsP DCPBH laser at different temperatures.

Spectra

p248

The spectra is current dependent. As you modulate from off to on, the spectra changes.

For long distance, single mode is essential, and what matters is single mode under modulation

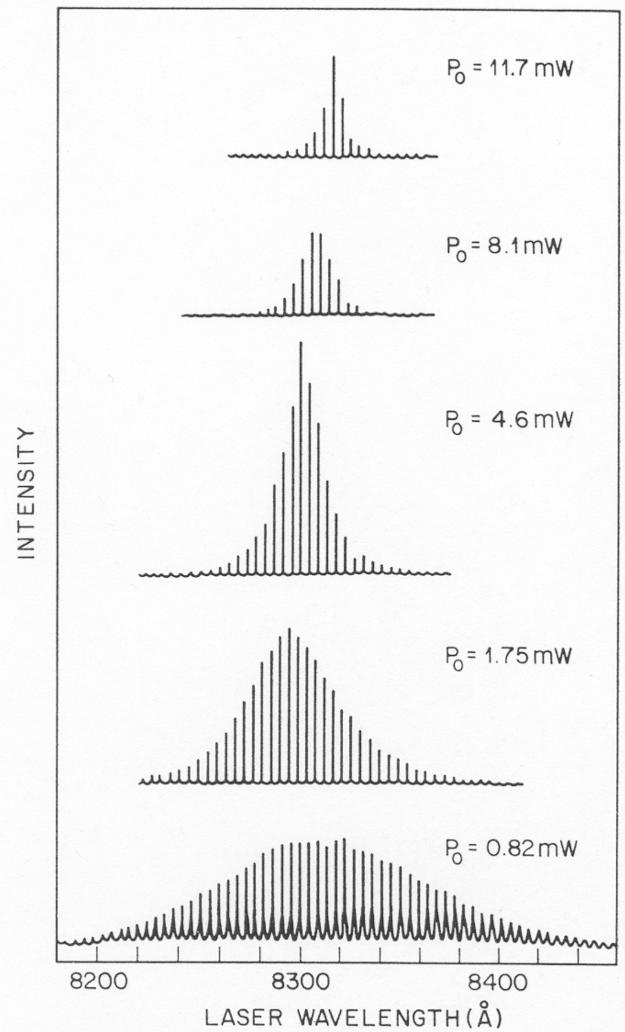


Fig. 6.6 Longitudinal-mode spectra of a gain-guided laser observed at several power levels. Experimental spectra for an index-guided laser are shown in Fig. 2.12. (After Ref. 35)

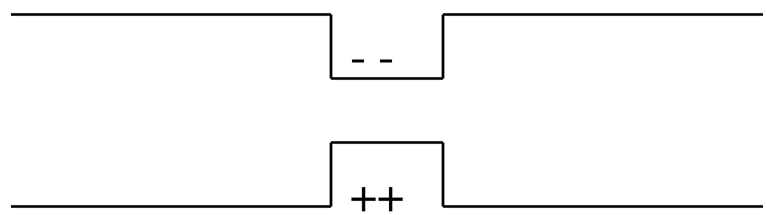
Semiconductor Emission Wavelength

- Emission wavelength depends on the bandgap energy (E_g) of semiconductor material
- Direct bandgap semiconductors are more efficient for light generation than indirect bandgap semiconductors (e.g., silicon)

	AlGaAs	InGaAsP
	.81 - .87 μm	1.0 - 1.65 μm

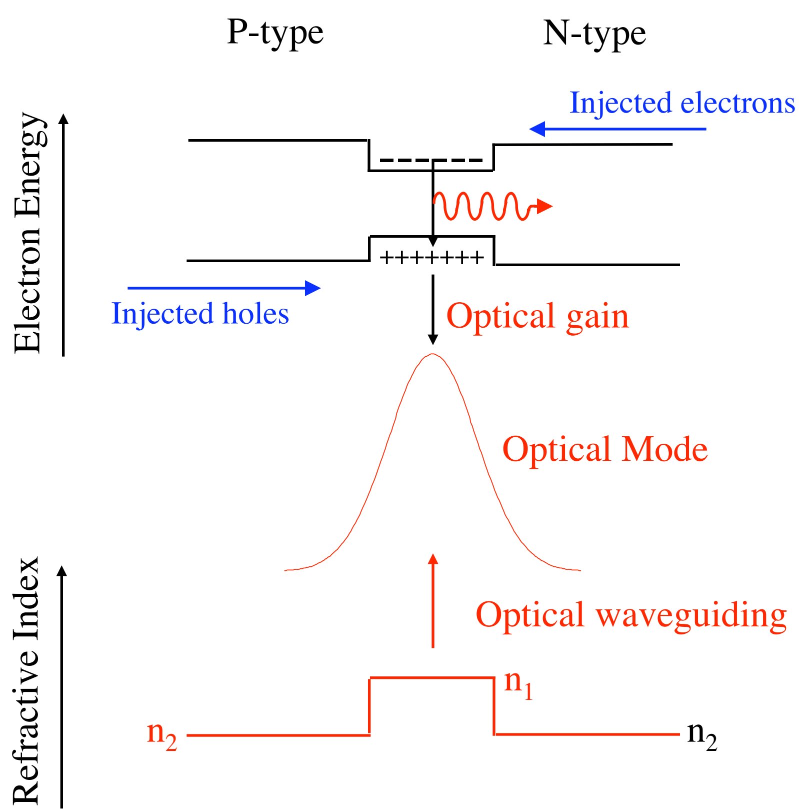
Double Heterostructure Lasers (Kroemer)

- Carriers diffuse away so it is difficult to get high gain
- A method of confining the carriers to a region in space is necessary
- Double heterostructure (proposed in 1964 but not implemented until 1968, which led to the first cw lasers).



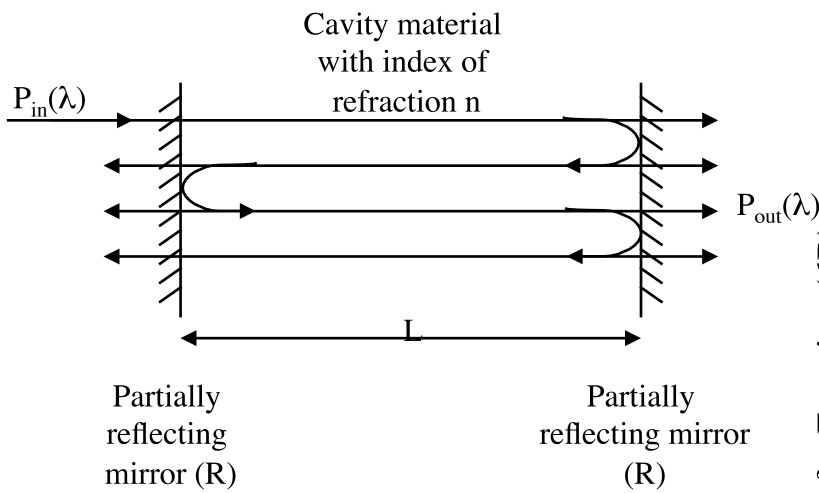
Optical and quantum confinement

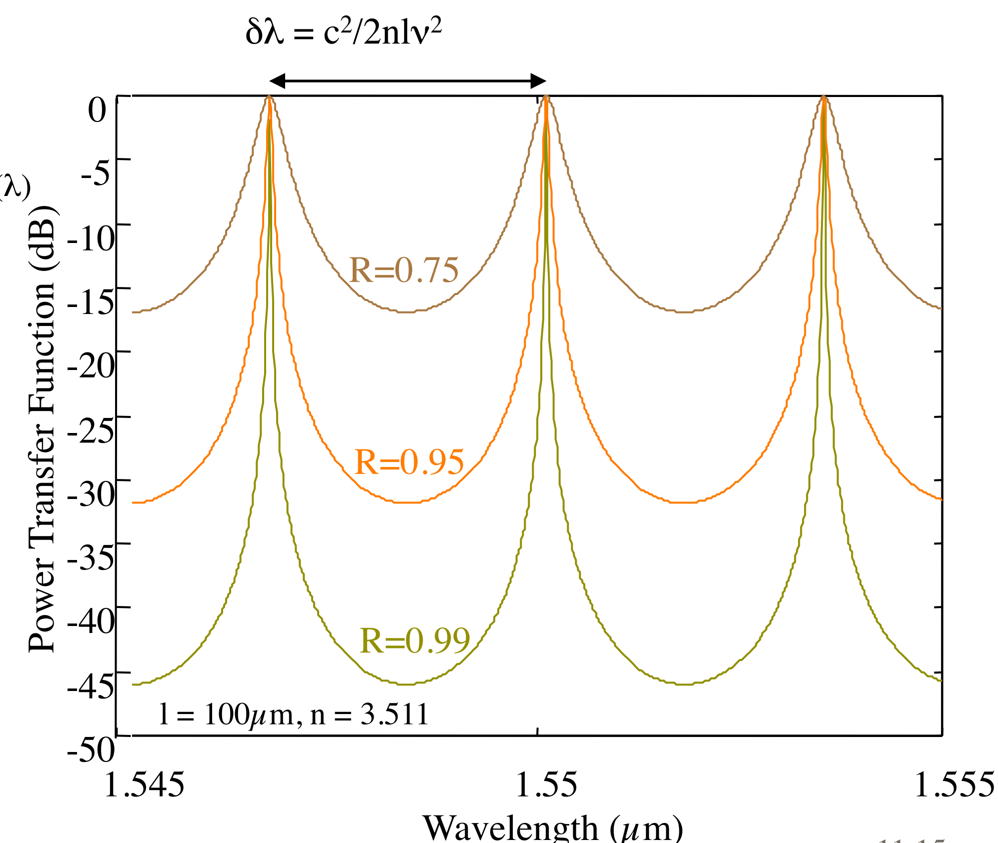
- A heterostructure is a p-n junction between materials with dissimilar bandgaps
- Used to confine: Carriers (efficiency) and Photons (waveguide)



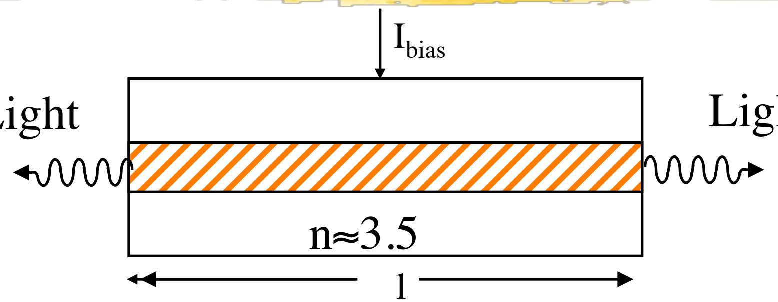
Fabry-Perot Cavities

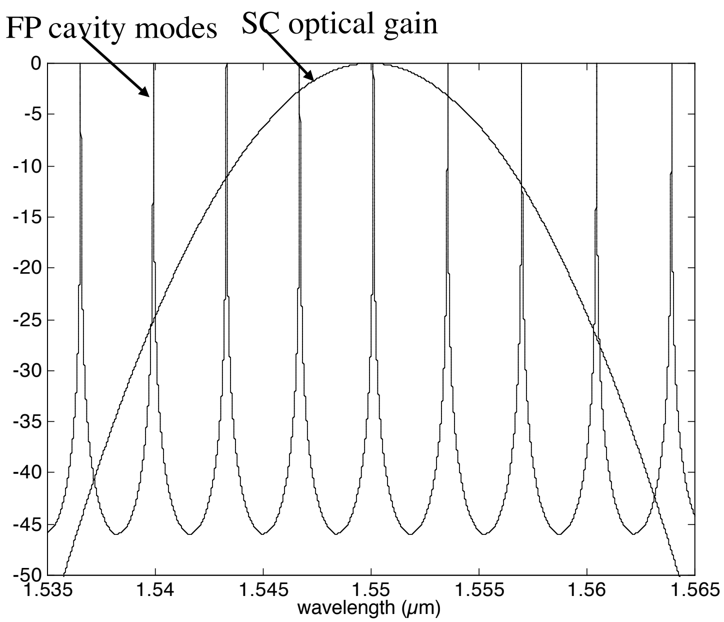
⇨ The equivalent of an electronic comb filter, but for optical frequencies, the Fabry-Perot (FP) cavity is used for feedback in lasers and as optical filters

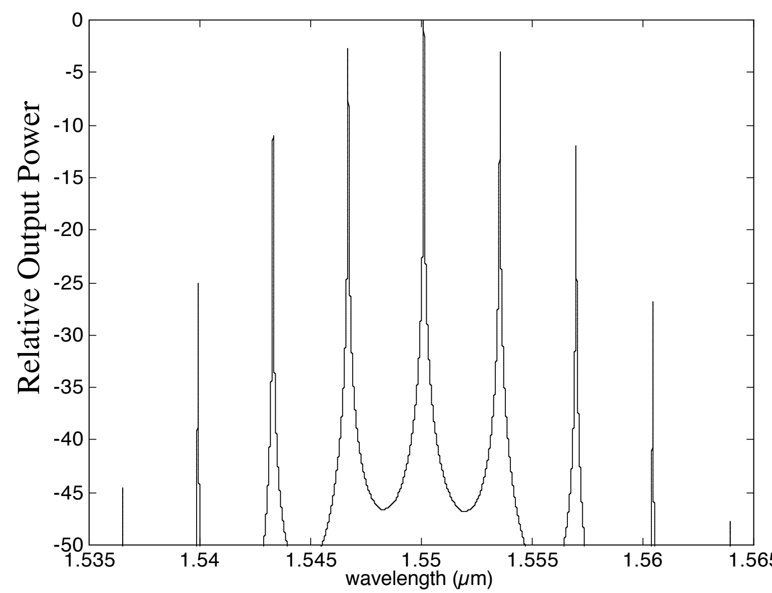




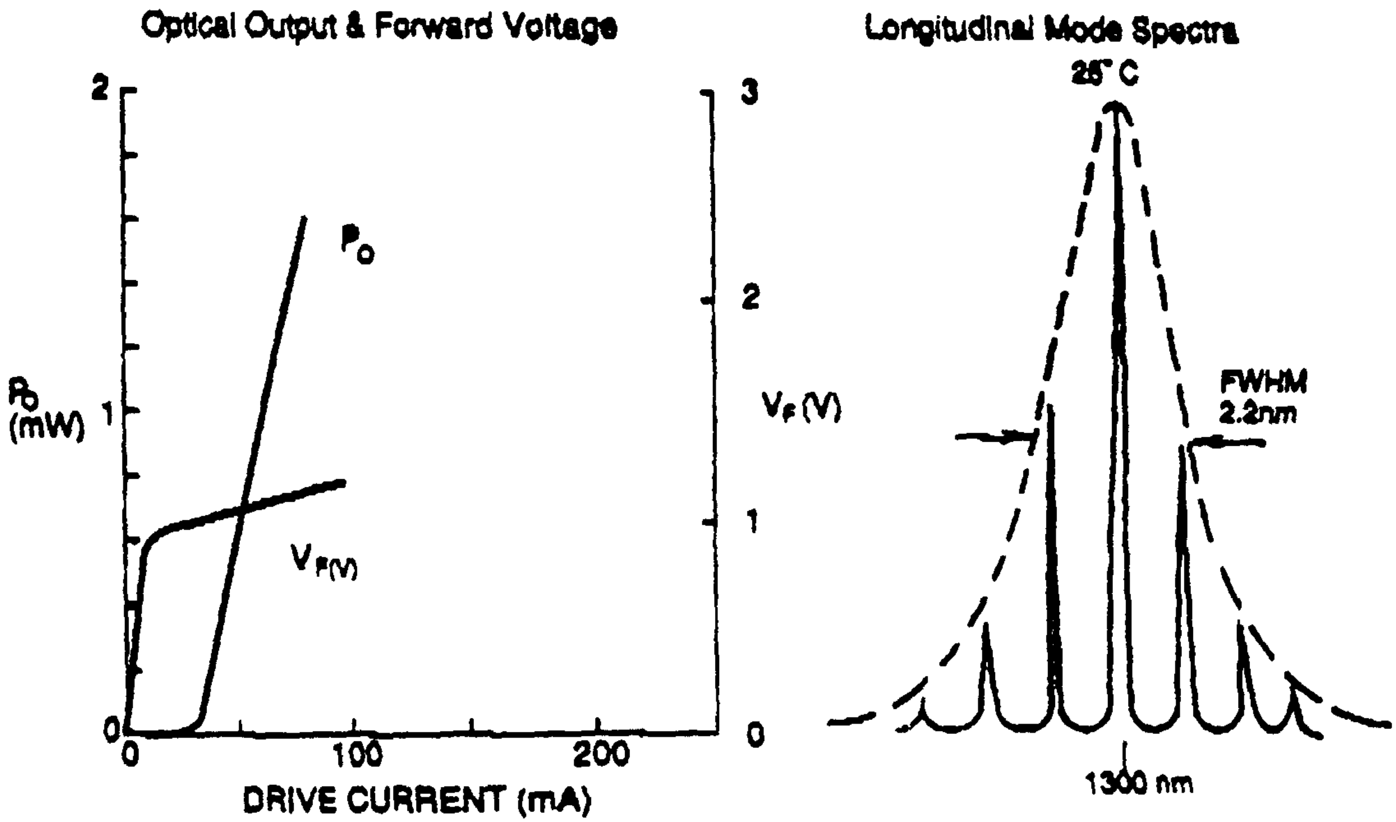
Multimode Fabry-Perot SC Lasers







FP SC Laser Output Characteristics



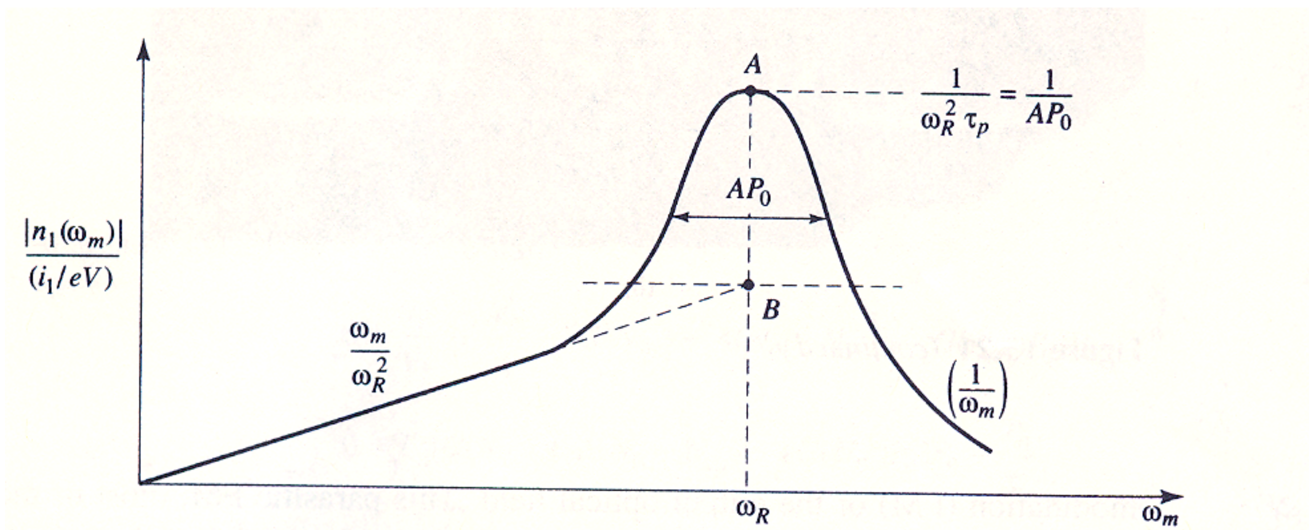
•1.3 μm multimode lasers are good for bit rates < 2Gbs and distances up to 100 km.

Carrier Density Modulation

⇨ Plotting the magnitude change in n_1 as a function of ω_m, we see the relaxation oscillation frequency introduced in the last lecture.

$$n_1(\omega_m) = -i\left(\frac{i_1}{Vq}\right)\frac{\omega_m}{\omega_m^2 - \frac{AP_0}{\tau_p} - i\omega_m\left(\frac{1}{\tau} + AP_0\right)}$$

$$\omega_R = \sqrt{\frac{AP_0}{\tau_p} - \frac{1}{2}\left(\frac{1}{\tau} + AP_0\right)^2}$$



Rate Equations

Neglecting the phase of the optical field, the length dependence of the carrier and photon densities, and the modal dependence; the rate equations for the averaged photon and carrier densities become:

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

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

Gain Suppression (Non-Linear Gain)

- Previously we talked about different effects that reduce the overall material gain.
- Yariv and Yeh differentiate between the following
  - ***Gain Saturation:*** Drop in gain population *N* due to increase in photon density
  - ***Gain Supression:*** Total carrier density *N* is constant but distribution of carriers as a function of energy or momentum changes with photon density. Former is called ***Dynamic Carrier Heating (DCH)*** and the later ***Spectral Hole Burning (SHB).***
- Rewriting the optical gain constant to include the ***gain supression factor*** ε by performing a Taylor Series Expansion about ($N=N_{th}$, P_0)

$$G(N,P) = G(N)(1 - \varepsilon P) \approx G(N_{th}) + A(N - N_{th}) - \varepsilon G(N_{th})P$$

Gain Suppression

- Re-writing the small signal photon density modulation term to include gain suppression

$$p_1(\omega_m) = \frac{-\Gamma_a A P_0 \left(\frac{i_1}{Vq}\right)}{\omega_m^2 - i\omega_m\left(\frac{1}{\tau} + AP_0 + \frac{\varepsilon P_0}{\tau_p}\right) - \left(\frac{AP_0}{\tau_p} + \frac{\varepsilon P_0}{\tau\tau_p}\right)}$$

- Example:

$$P_0 = 1.2\times 10^{21} \text{ photons/m}^3$$

$$A = 2\times 10^{-12} \text{ m}^3\text{/s}$$

$$\tau_\text{p} = 10^{-12} \text{ s}$$

$$\tau = 10^{-9} \text{ s}$$

$$\varepsilon = 10^{-23} \text{ m}^3$$

$$\frac{\varepsilon P_0}{\tau_\text{p}} = 1.2\times 10^{10}\text{s}^{-1} \;\square\; \text{A}P_0$$

Gain Suppression

- Under the operating condition that $\varepsilon P_0/\tau_p >> AP_0$

$$\omega_R \approx \sqrt{\frac{AP_0}{\tau_p} - \frac{\varepsilon^2 P_0^2}{2\tau_p^2}}$$

- So considering gain suppression, P_0 and ω_R reach maximum values at

$$\left(P_0\right)_{\max} = \frac{A\tau_p}{\varepsilon^2}$$

$$\left(\omega_R\right)_{\max} = \frac{A}{\sqrt{2}\varepsilon}$$

- Using the values from the previous example

$$\left(P_0\right)_{\max} = 2 \times 10^{22} \text{ photons/m}^3$$

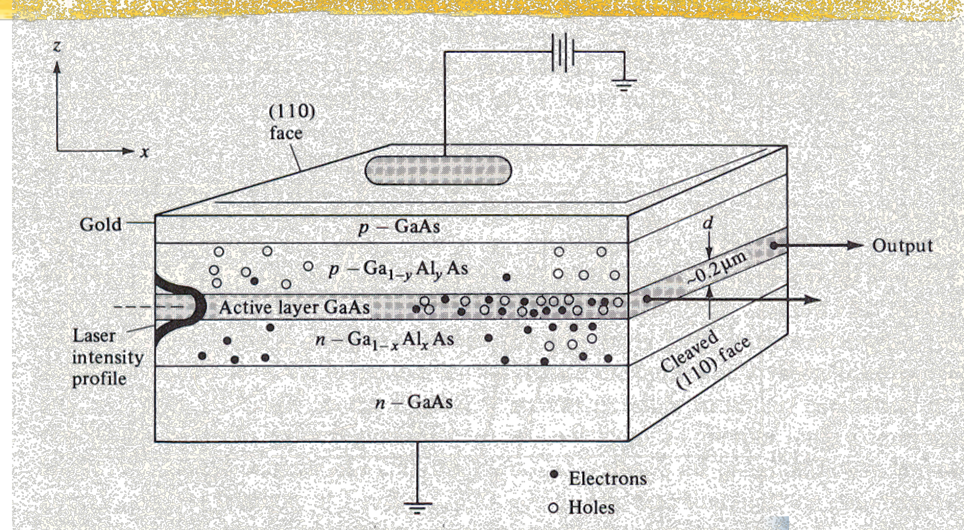
$$\left(f_R\right)_{\max} = \left(\frac{\omega_R}{2\pi}\right)_{\max} = 2.24 \times 10^{10} \text{ Hz}$$

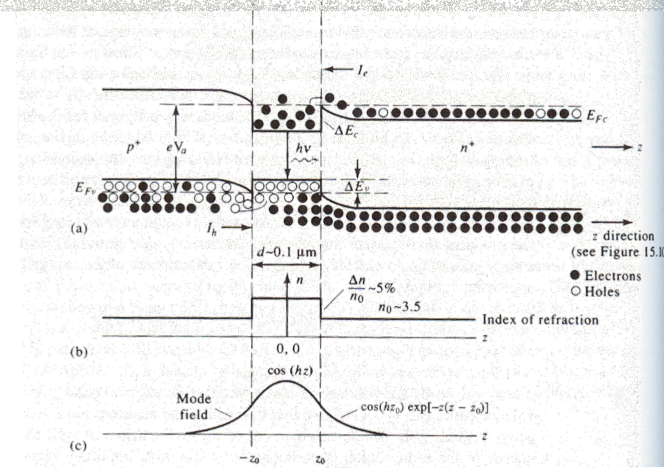
GaAs/GaAlAs and GaInAsP Lasers

- 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$_x$As 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***

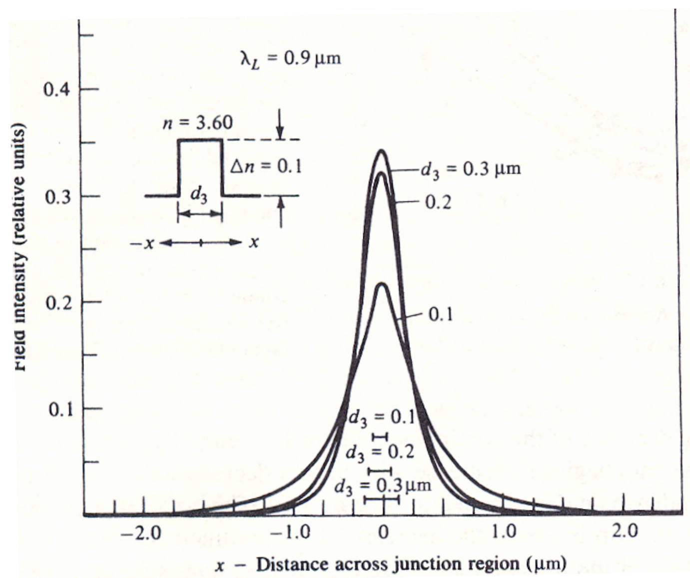
Modal Gain

- 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, <u>Photonics</u>

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

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

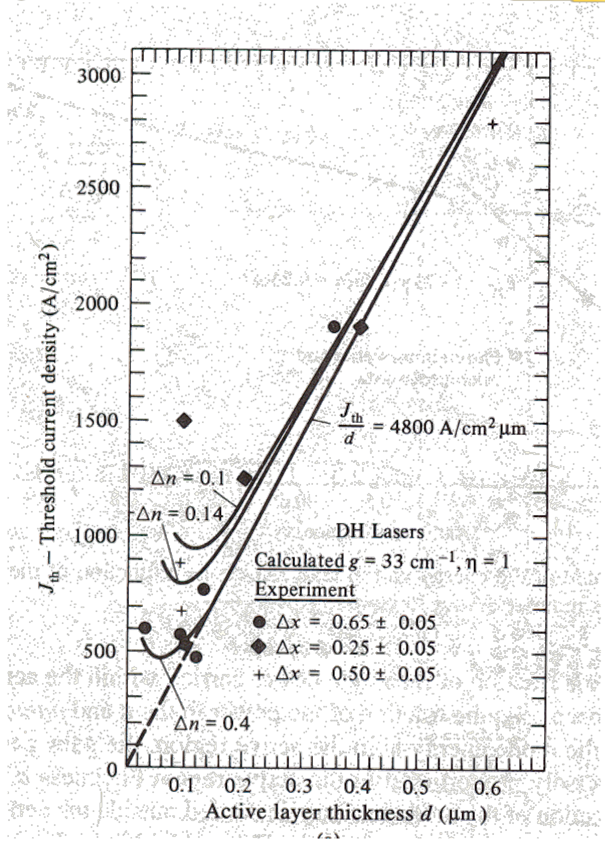
- Given losses, R and confinement factors, we can calculate the gain γ required for threshold.
- Under steady state, the carrier injection rate equals the electron-hole recombination rate, and the electron hole recombination rate can be calculated for the required γ

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

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

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

- 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, <u>Photonics</u>

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

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

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

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

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