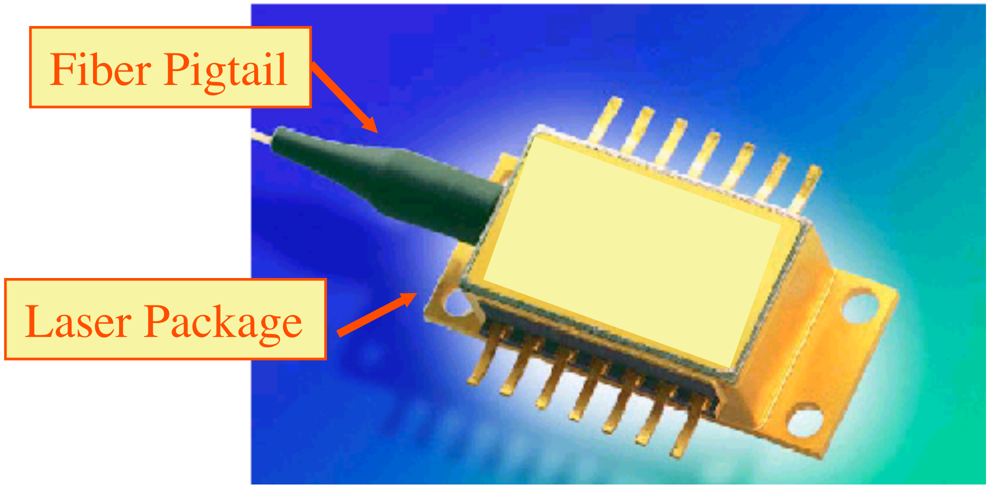
Lecture 4: Semiconductor Lasers

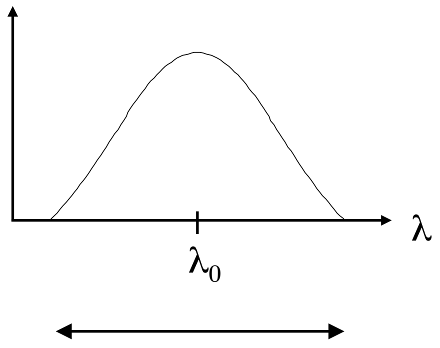
Semiconductor Optical Sources

- The optical sources practically used in optical communications are based on semiconductor devices
- The generated optical signal is to be efficiently coupled to the output optical fiber
  - Other kinds of sources (non-semiconductor) and/or free space coupling is sometimes done in R&D labs, but only for advanced and prototypal research
  - All commercial sources comes in very compact packages, and are fiber pigtailed in the factory
  - Pigtailing and packaging is one of the most critical and expensive issues for these devices



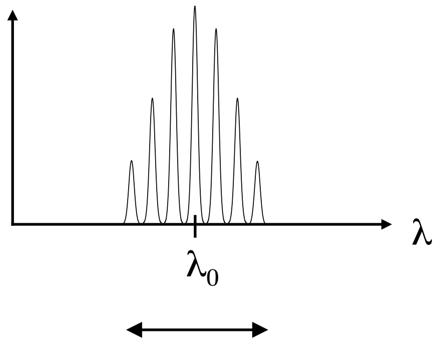
Semiconductor Optical Sources

Light Emitting Diode (LED)



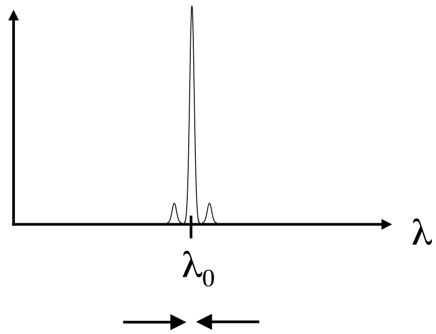
$\Delta\lambda \approx$ 30-100 nm

Multimode Laser Diode



$\Delta\lambda \approx$ 10 nm

Single Mode Laser Diode



$\Delta\lambda \approx$ .01 nm

The linewidth, $\Delta\lambda$, is often measured at the full width half maximum point (FWHM)

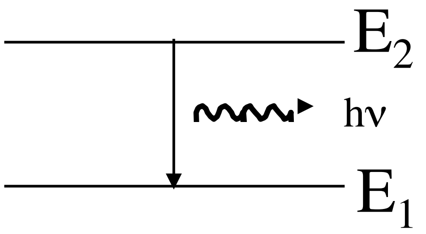
Characteristics

Characteristic	Description
Number of longitudnal modes	Number of optical frequencies laser emits. Plays a key role in both laser cost and how fiber dispersion will limit link bit rate.
Side Mode Suppression Ratio (SMSR)	A measure of how good a single mode laser is.
Threshold current	The minimum current required to turn on the laser. Low values are key to decrease transmitter power dissipation
Laser Noise	A measure of how random the optical laser output is. This characteristic can determine the ultimate performance of a link.
Linewidth	A measure of how noisy the laser. Plays a key role in how dispersion and crosstalk limits the transmission bit rate and capacity.
Wavelength	Determines the dispersion and loss operating points in the fiber and other network components.
Modulation Bandwidth	Determines the bit rate that can be attained by current modulation.
Chirp	A measure of how the optical output frequency changes with current modulation. Impacts transmission bit rate.
Linearity	Ability to reproduce and analog signal with low distortion.
Fiber Output Power	Power launched into fiber to achieve high signal-to-noise ratio.
Wavelength Tunability	The ability to tune the output wavelength over a wide range.
Long Term Stability	In terms of wavelength, output power and other key factors.

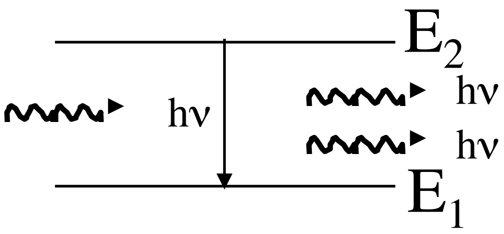
Basic Laser Theory

Optical Emission

- E_2 is the bottom of the conduction band and E_1 is the top of the valance band

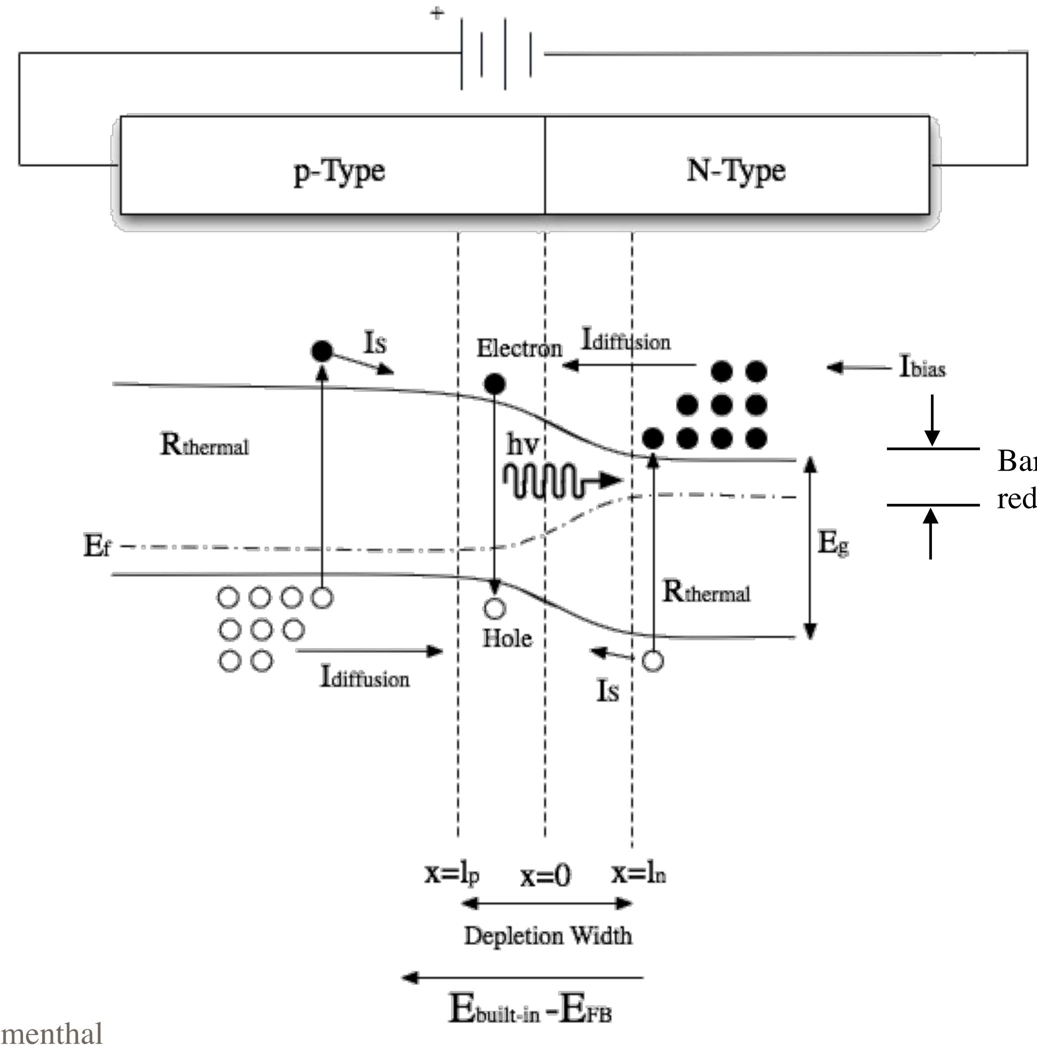


- Radiative recombination
- Photon spontaneously emitted with energy $E_{photon} = h\nu = E_2 - E_1$



- Incident photon causes radiative recombination
- Two photons with same characteristics created

Forward Biased Semiconductor p-n Junctions



Barrier has been
reduced by forward bias

Optical Gain in Semiconductors (1)

- For plane wave propagation in a complex medium, with k_0 the free space wave vector and n’ and n’’ the real and imaginary part of the refractive index respectively

$$\beta = \kappa_0 \left(n' + jn'' \right)$$

$$\kappa_0 = \frac{\omega}{c} = \frac{2\pi}{\lambda}$$

- The optical gain (loss) for a plane wave propagating in a semiconductor in the z-direction can be approximated by

$$g = -\alpha = \frac{1}{I}\frac{dI}{dz} = 2\kappa_0 n''$$

Optical Gain in Semiconductors (2)

- The band structure and electron probability distribution is given by

$$W_c(E) = \left[1 + \exp\left(\frac{E - E_{Fc}}{k_B T}\right)\right]^{-1}$$

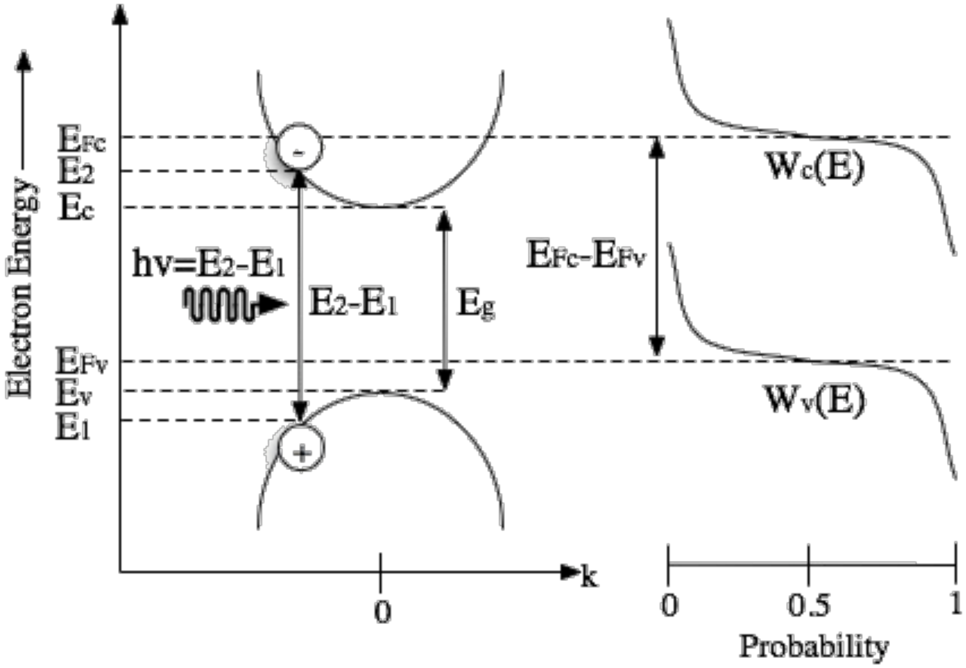
$$W_v(E) = \left[1 + \exp\left(\frac{E - E_{Fv}}{k_B T}\right)\right]^{-1}$$

$$N = N_c \frac{2}{\pi}\int_{E_c}^{\infty} Z_c(E) W_c(E)\, dE$$

$$P = N_v \frac{2}{\pi}\int_{-\infty}^{E_v} Z_v(E)\left[1 - W_v(E)\right] dE$$

Carrier density

Density of states

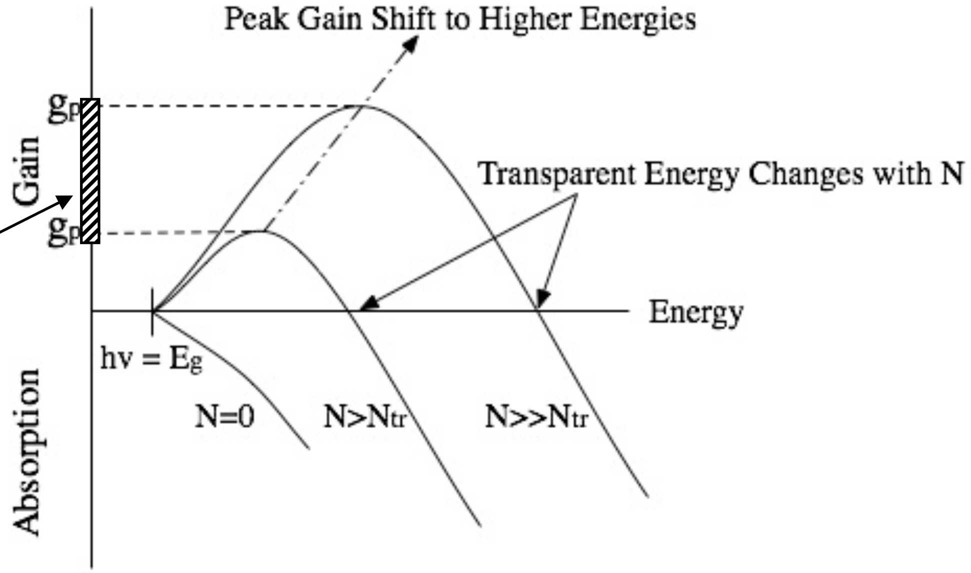


Optical Gain in Semiconductors (3)

- Optical gain by stimulated emission for a photon of energy hν exceeds band to band absorption if

$$E_{Fc} - E_{Fv} \geq h\nu = E_2 - E_1 \geq E_g$$

- The gain is wavelength dependent with a peak gain that shifts as a function of carrier density.



Can approximate g_p as a function of N over small range

$$g_p = a\left(N - N_{tr}\right)$$

Optical Gain in Semiconductors (4)

- The injected carrier density N is determined by the laser current *I*, the recombination rate *R(N)* and the active region volume V

$$I = qR(N)V$$

$$R(N) = \frac{N}{\tau_s} + BN^2 + CN^3$$

$$\tau_n = \frac{N}{R(N)}$$

where $A=N/\tau_s$ is the linear non-radiative recombination rate, B is the radiative bimolecular (band-to-band) recombination rate and C is the non-radiative Auger recombination rate

- Note: We will see that while the gain is coupled to the carrier density, the carrier density is coupled to the photon density and therefore to the gain. This coupling will lead to nonlinear gain or gain saturation, as will be discussed later in the carrier rate equations.

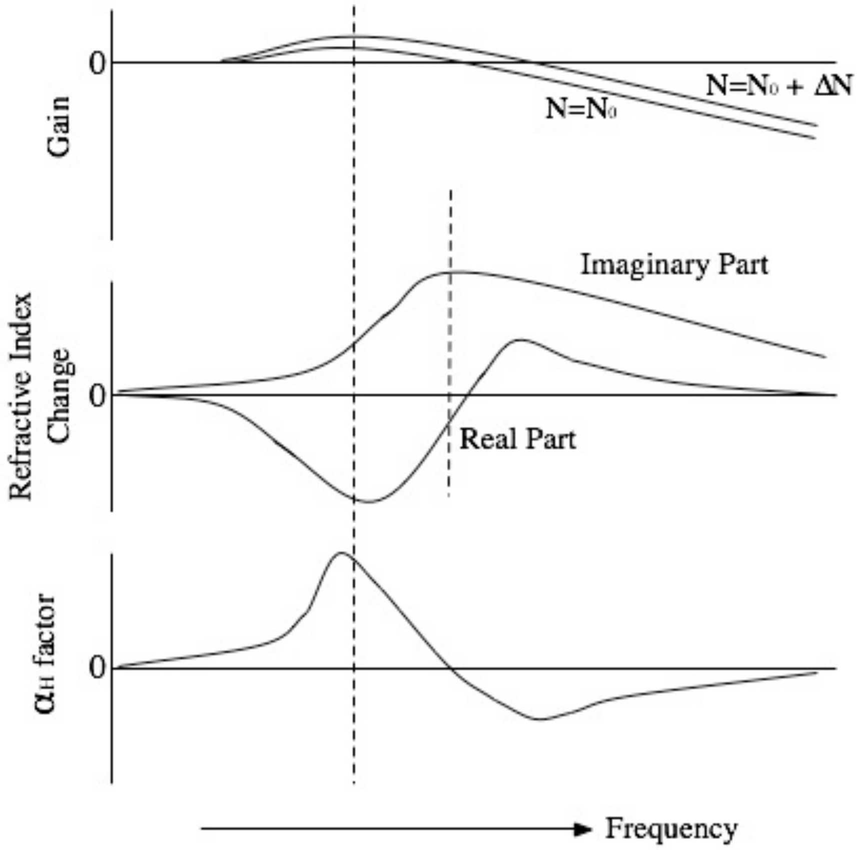
Coupling between Optical Gain and Phase

- The Kramers-Kronig relations tell us that changes in the in the imaginary (Δg) and real parts of the refractive index (Δn) are related by

$$\Delta n'(\omega) = \frac{c}{\pi} P \int_0^\infty \frac{\Delta g(\omega')}{\omega'^2 - \omega^2} d\omega'$$

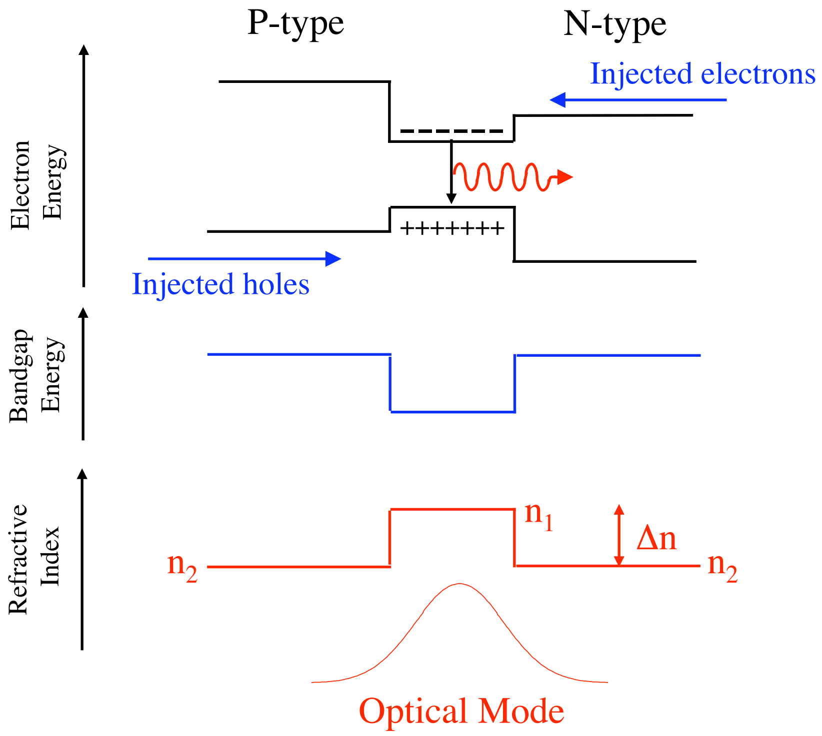
- The coupling between gain and phase is described by the linewidth enhancement (or alpha) factor

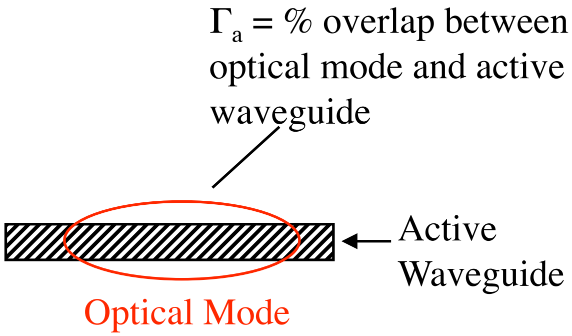
$$\alpha_H = -\frac{\partial n' / \partial N}{\partial n'' / \partial N}$$



Optical and Carrier Confinement

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

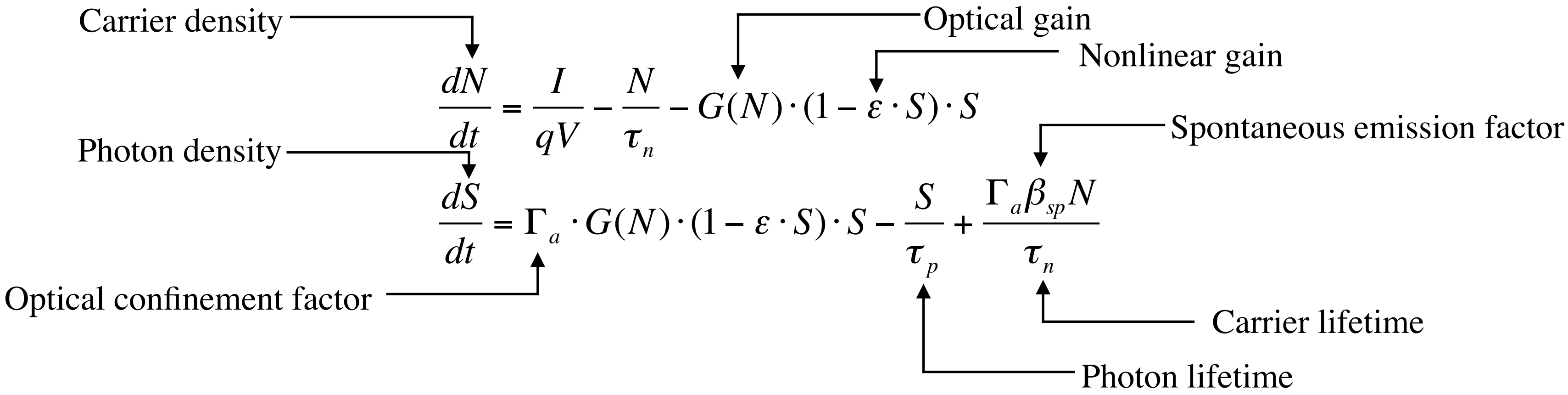



Γ_a = % overlap between optical mode and active waveguide

Laser Rate Equations

⇨ Define the laser output power P(t), the current I(t), the active gain volume V, and the carrier and photon densities N(t) and S(t) respectively.

⇨ The dynamics of carrier and photon density in the semiconductor laser cavity is governed by couple rate equations



Carrier density

Optical gain

Nonlinear gain

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

Spontaneous emission factor

Photon density

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

Optical confinement factor

Carrier lifetime

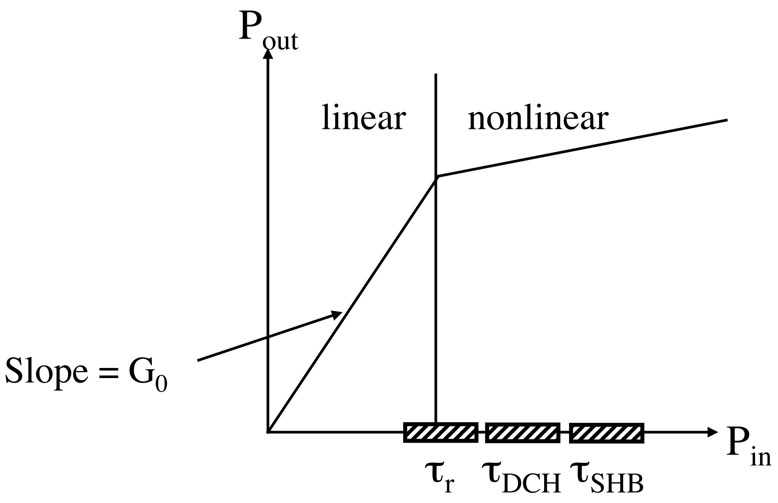
Photon lifetime

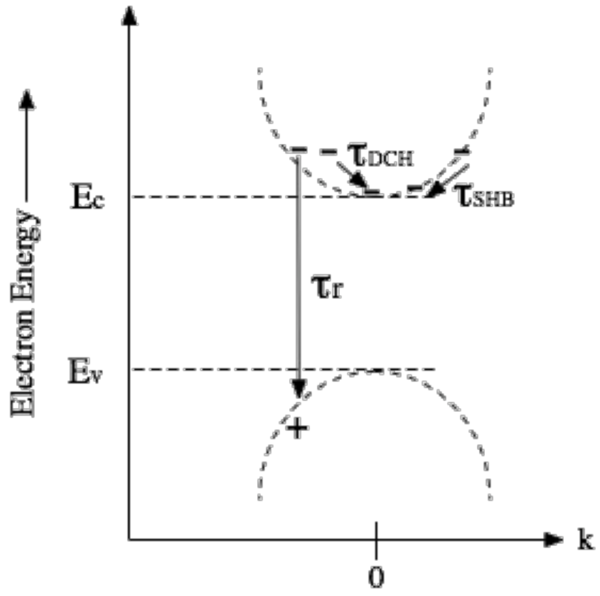
Nonlinear Gain (Gain Compression)

- Gain saturation (recovery) is governed by the rate that carriers can be replenished.
  - Band to band is governed by (τ_r)
  - Carriers cool from levels within band to band-edge by giving up energy to phonons (τ_{DCH})
  - Carriers scatter off one another, changing momentum and energy along the band-edge (τ_{SHB})

$$\varepsilon = \frac{1}{\tau_r} + \frac{1}{\tau_{DCH}} + \frac{1}{\tau_{SHB}}$$

$$\tau_r \approx 1ns, \tau_{DCH} \approx 650\,fs, \tau_{SHB} \approx 50\,fs$$





Steady State Solutions to Rate Equations

- Setting the rate equations equal to zero

$$\frac{dN}{dt}=\frac{dS}{dt}=0$$

- and the cavity photon density S=0, we get the below (at) threshold condition

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

$$I_{th}=\frac{qVN_{th}}{\tau_n}=qVR(N_{th})$$

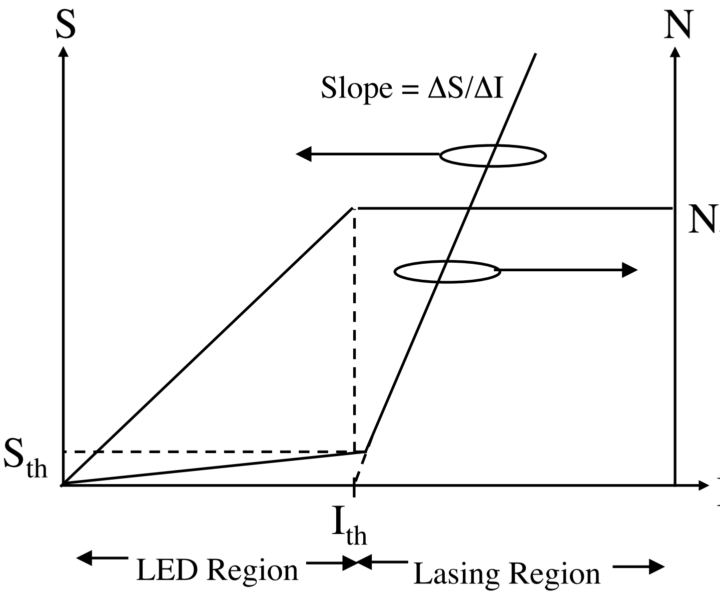
- using the linear gain relation, and at threshold gain = total losses

$$N=N_{tr}+\frac{g_p(N)}{a}$$

$$N_{th}=N_{tr}+\frac{g_p(N_{th})}{a}=N_{tr}+\frac{\alpha_{total}}{a}$$

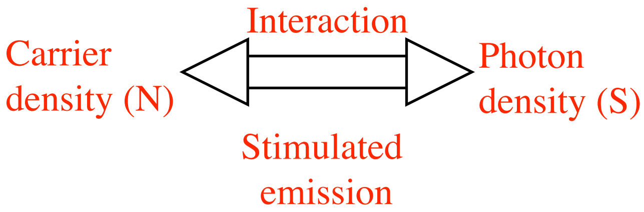
- At and above threshold, with non-zero S and assuming linear operation (ε = 0)

$$S=\frac{I}{qVG(N_{th})}-\frac{R(N_{th})}{G(N_{th})}=\frac{I-qVR(N_{th})}{qV\alpha_{total}}=\frac{I-I_{th}}{qV\alpha_{total}}$$



Small Signal Modulation

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



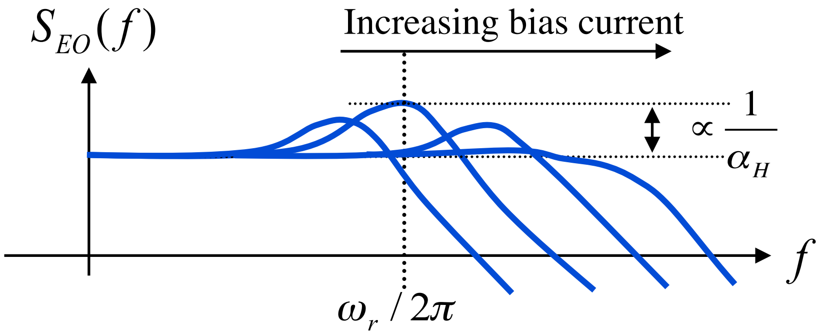
$$\frac{dN}{dt} = \frac{I}{qV} - \frac{N}{\tau_n} - G(N)\cdot(1-\varepsilon\cdot S)\cdot S$$

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

- 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.



Large Signal (Digital) Modulation

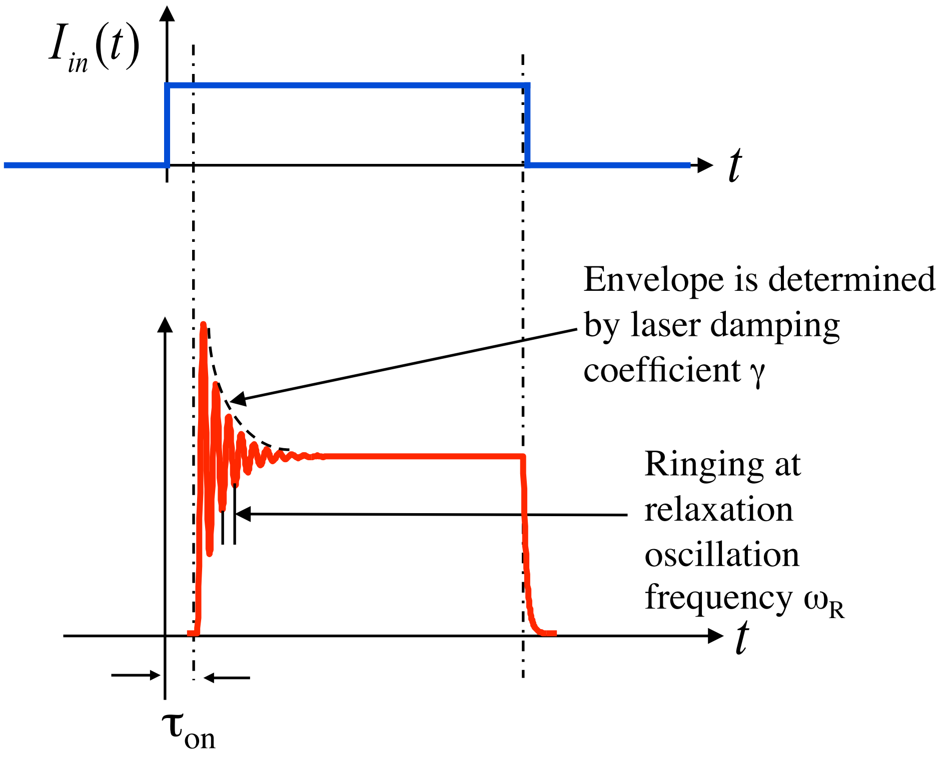
- Pulse response of a directly-driven semiconductor laser

- 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

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

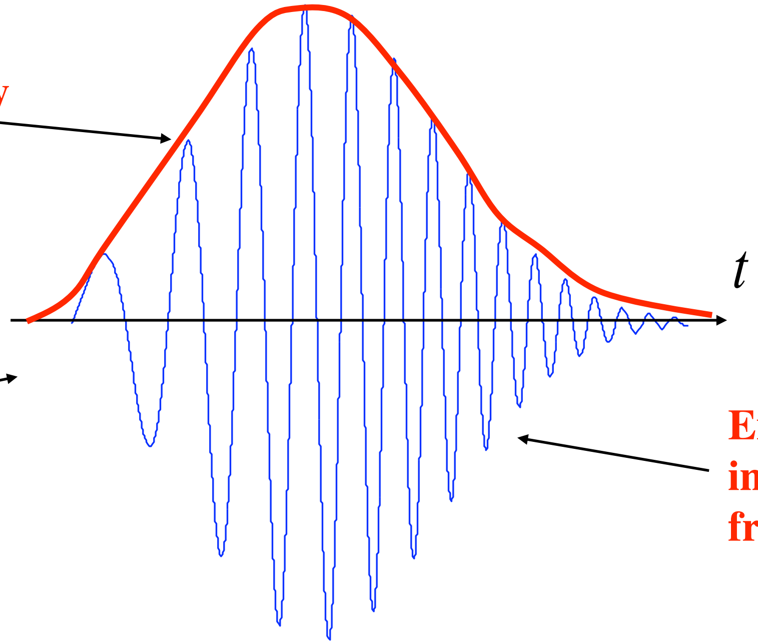


Envelope is determined by laser damping coefficient γ

Ringing at relaxation oscillation frequency ω_R

Laser Chirp

- Another important parameter is the laser frequency chirp (frequency shift)
- Chirp will limit the bit-rate-distance product that a link can support
- Chirp occurs when directly driving a laser, the change in carrier density changes the effective index of refraction, and thus the oscillation <u>optical</u> frequency
    - This can be interpreted as a bit-synchronous phase or frequency modulation



Optical Intensity (field envelope)

Actual Optical Field

Example of increasing frequency

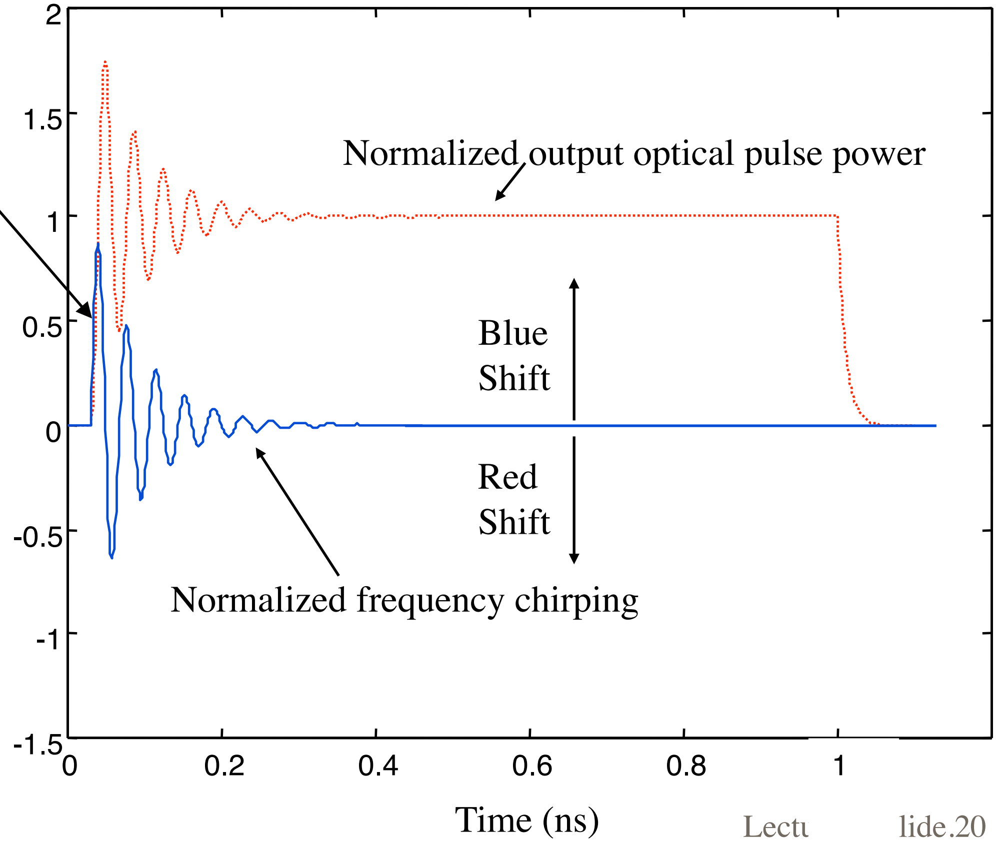
SC Laser direct modulation

- As the laser current is changed between the low and high states, the laser carrier density changes and there is a resulting time dependent phase change.
- The time dependent phase changes leads to an instant frequency shift called **frequency chirp**.

$$\Delta\nu(t) = -\frac{\alpha}{4\pi}\left(\underbrace{\frac{1}{P}\frac{dP}{dt}}_{(1)} + \underbrace{\frac{2\Gamma\varepsilon}{V\eta h\nu}\Delta P(t)}_{(2)}\right)$$

(1) Dynamic chirp: wavelength shift associated with on-off modulation

(2) Adiabatic chirp: Steady-state emission frequency difference between on and off states



Multi- and Single-Mode Lasers

Fabry-Perot Cavities (1)

- 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

- For wavelength dependent mode gain (Γg_a) and internal optical losses (α_i), define net gain $g_{net} = \Gamma g_a - \alpha_I$.
- The propagation constant for a plane wave propagating in the cavity is $\beta = \kappa_0 n'_{eff} + j\frac{g_{net}}{2}$
- The forward and backward propagating waves can be written as $S^+(z) = S^+(0)e^{g_{net}z}$

$$S^-(z) = S^-(0)e^{-g_{net}z}$$

- The phase matching condition for steady state oscillation requires all amplitudes and phases for each round trip to constructively interfere $r_1 r_2 e^{-2j\beta L} = 1$
- For end mirror loss $\alpha_m = \frac{1}{2L}\ln\frac{1}{R_1 R_2}$

- The oscillation condition becomes

$2j\beta L + \alpha_m L = 2j\pi N$, where N is an integer denoting longitudnal mode number

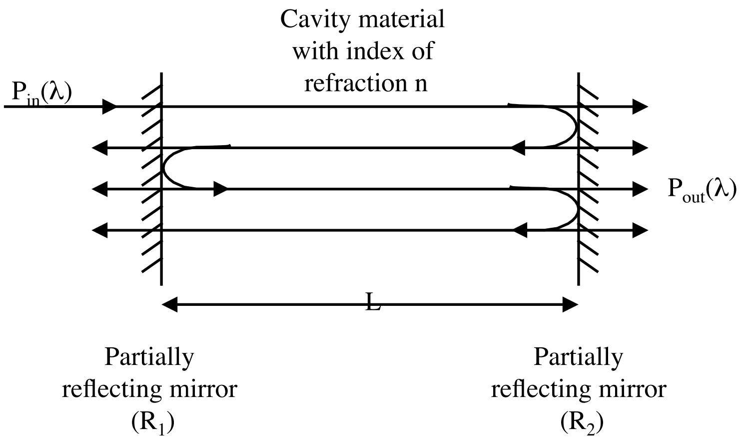
- Defining cavity roundtrip gain $g_c = g_{net} - \alpha_m$
- The real part of oscillation condition gives $g_c = 0$
- And $\Gamma g_a - \alpha_i - \alpha_m = 0$

- Defining the total cavity loss as $\alpha_{total} = \alpha_i + \alpha_m$
- Then $g_c = g_{eff} - \alpha_{total} = 0$
- And the resonance condition for the cavity is

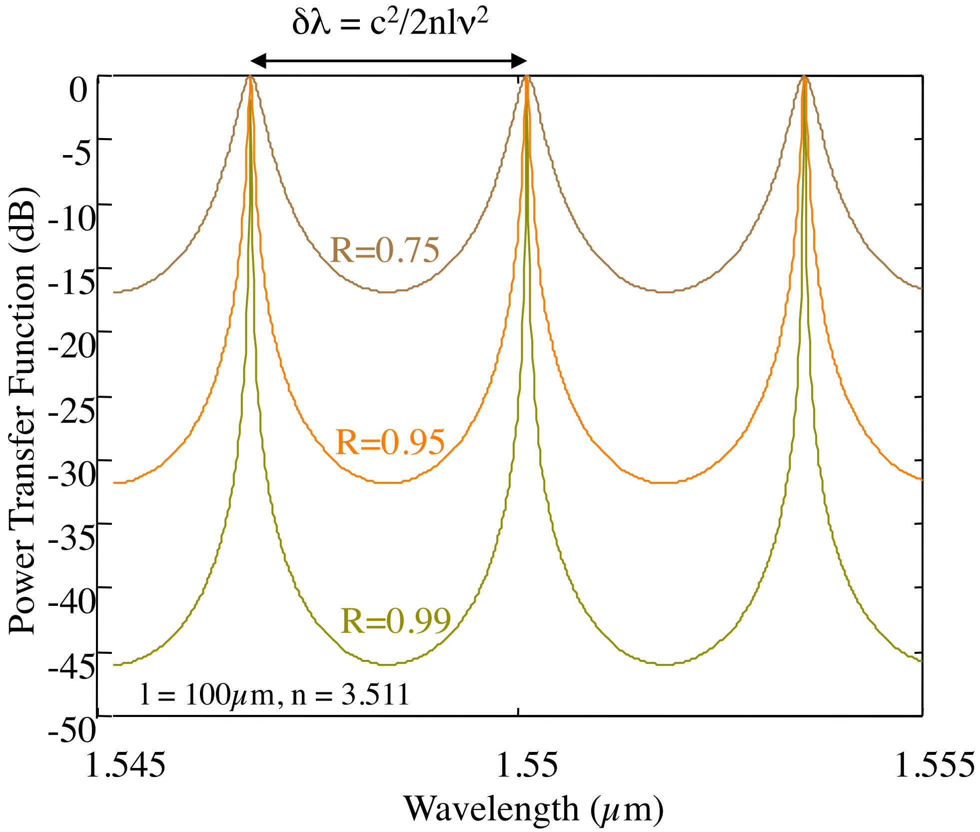
$$\lambda_n = \frac{2n'_{eff}(\lambda_n)L}{N}$$

$$\Delta\lambda_m = \lambda_n - \lambda_{n+1} \square \frac{\lambda_N^2}{2n_{g,eff}L}$$

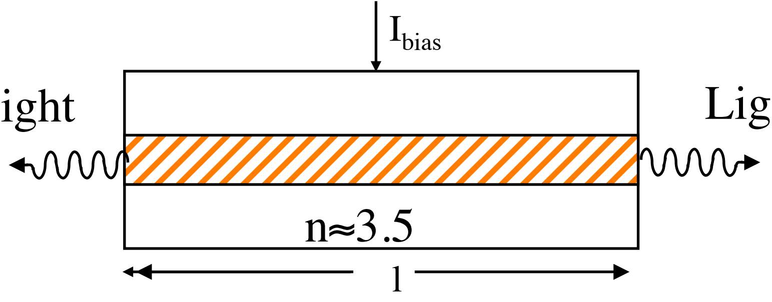
$n_{g,eff}$ = effective group index

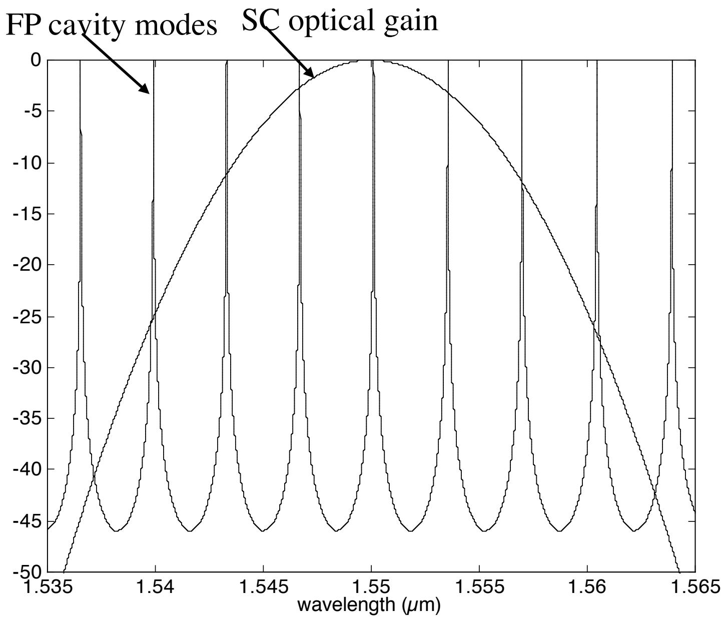


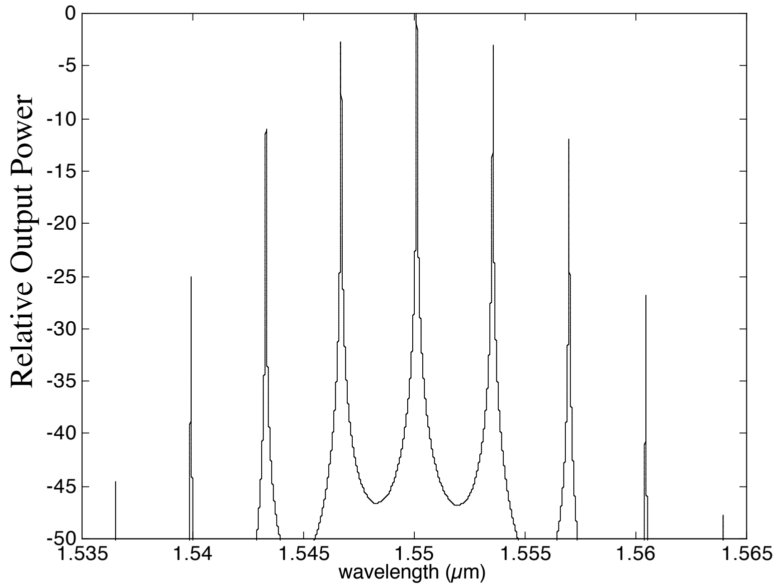
Fabry-Perot Cavities (2)



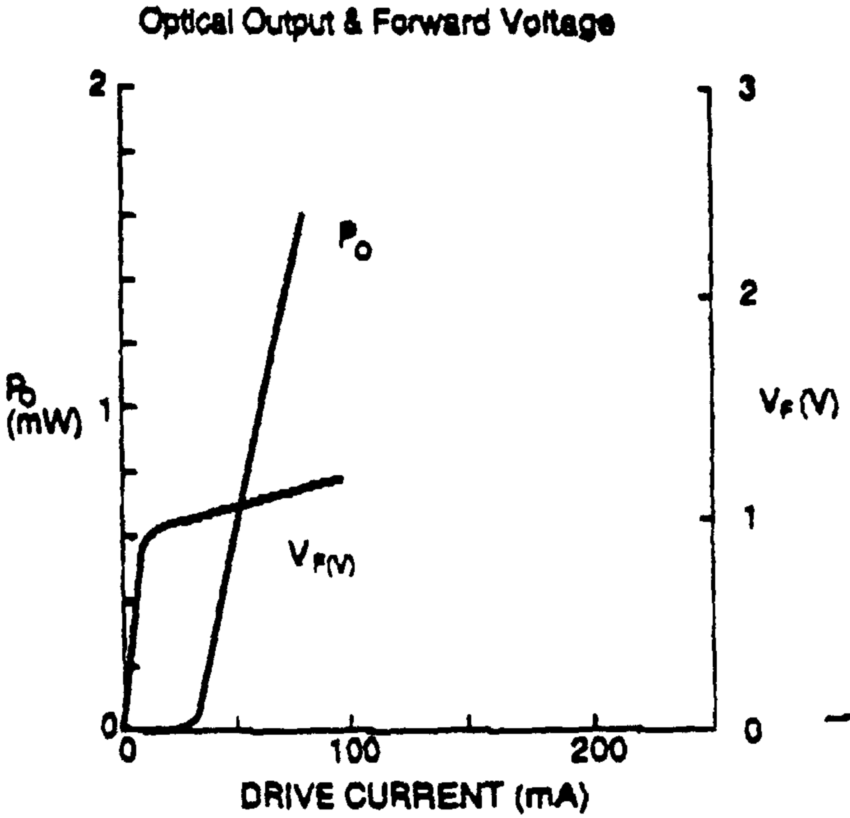
Multimode Fabry-Perot SC Lasers



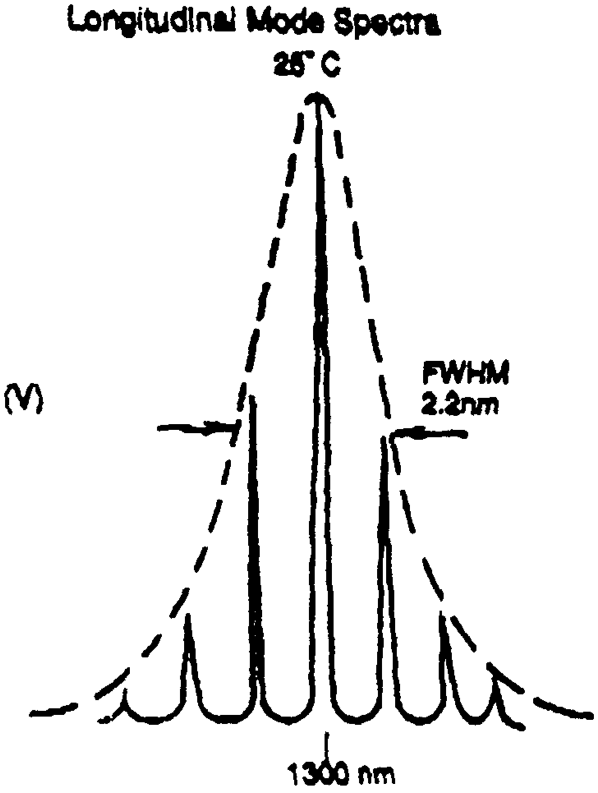




FP Laser Output Characteristics



Optical Output & Forward Voltage



Longitudinal Mode Spectra

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