Lecture 12 -Semiconductor Sources and Transmitters

Reading and Homework

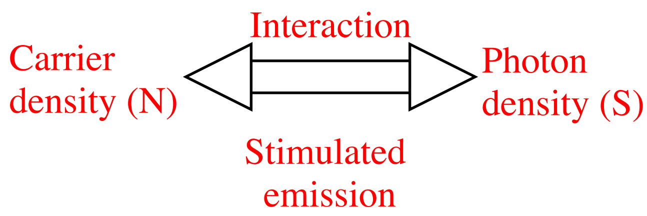
- Read Chapter 3 of Agrawal

Direct modulation of lasers

- Direct modulation: the information signal is directly applied to the laser driving current
- Advantage: lower cost with respect to external modulation
- Drawbacks: larger optical spectrum-> dispersion limit
  - A change in driving current changes carrier density
  - A change in carrier density modifies the effective index of refraction
  - A change in the effective index of refraction changes the laser resonant frequency
- Thus a change in $I(t)$ corresponds to a change in the output instantaneous optical frequency $f_{ist}(t)$
- This effect is characterized by the laser chirp parameter
  - Typical values: A DFB laser with a CW linewidth of 10 MHz, can have up to 1 nm (125 GHz) of spectral width under direct modulation

Small Signal Modulation

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



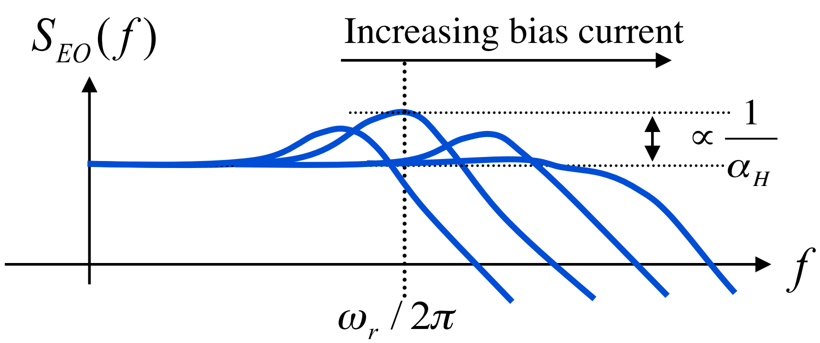
$$\frac{dN}{dt} = \frac{I}{qV} - \frac{N}{\tau_n} - G(N)\cdot(1-\varepsilon\cdot S)\cdot S$$

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

- 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.



Non-Infinite Extinction Ratio

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

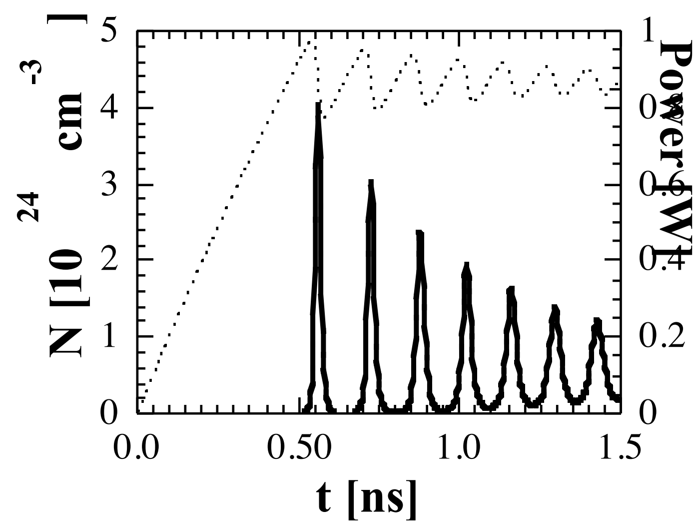
Large Signal Modulation
Step Response

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

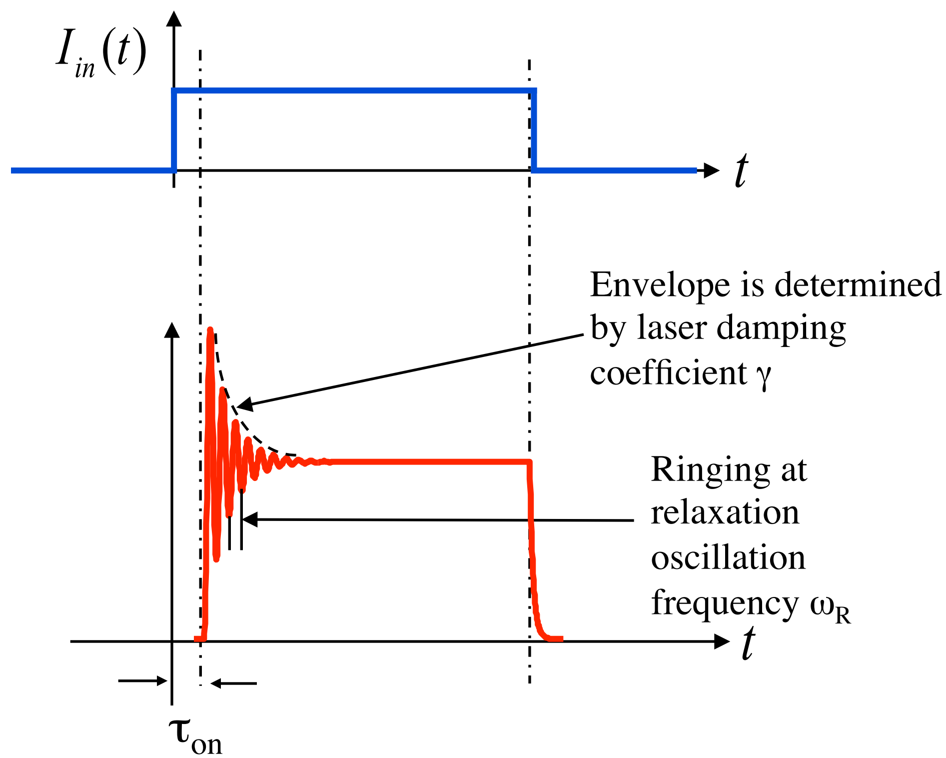
- Pulse response of a directly-driven semiconductor laser

- Laser turn-on delay τ_D is determined by drive circuit/laser combination.
  - Determined by the "zero" current level (below or above threshold)

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

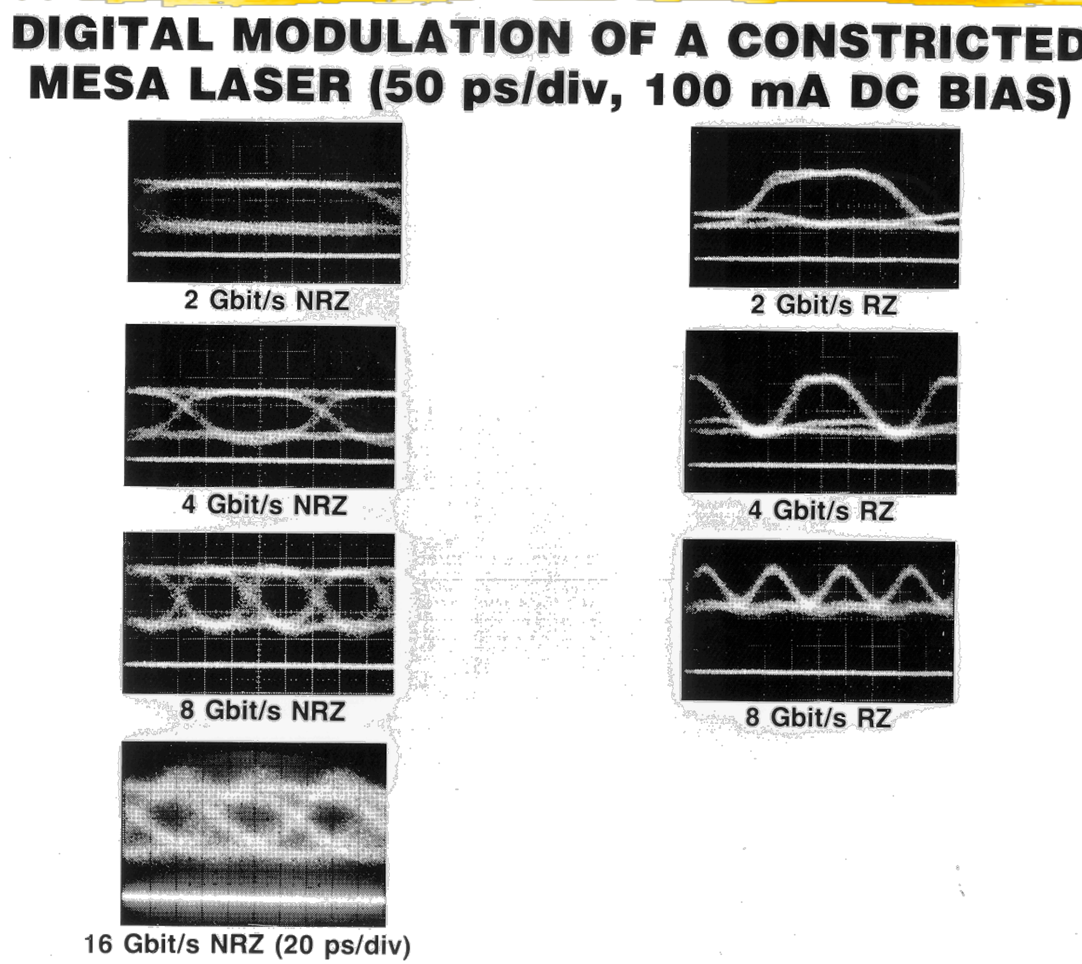
- Want α to dampen out relaxation oscillation well within the bit interval.
  - Choose I_{bias} to set frequency and magnitude of relaxation oscillation relative to bit period

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



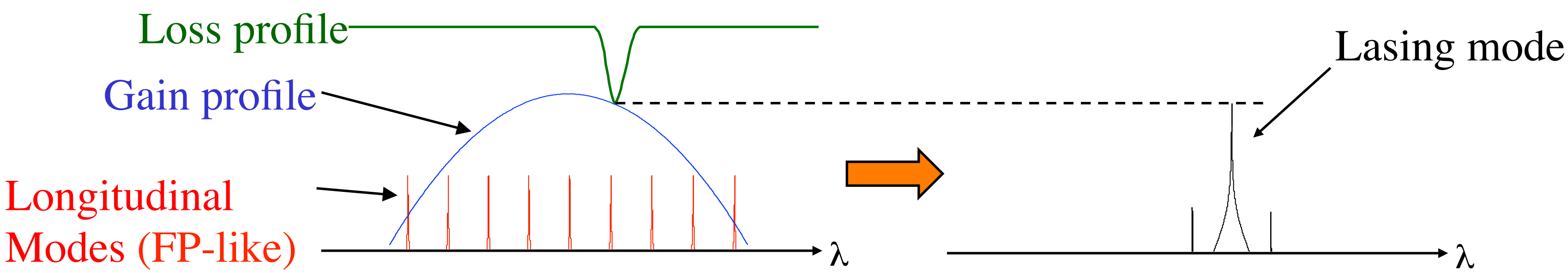
Digital Modulation

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



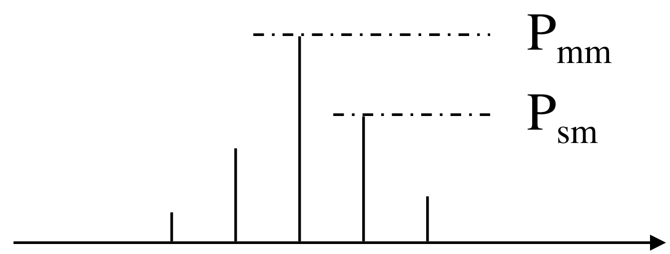
Single Mode Semiconductor Lasers

- Utilize design that reduces loss for one mode only



- Side Mode suppression ratio (SMSR)

$$SMSR = \frac{P_{\text{Main mode}}}{P_{\text{Side mode with mode power}}} = \frac{P_{mm}}{P_{sm}}$$



Far Field

•A single mode far field is important for efficient coupling to optical fiber. A far field that changes with current means pattern effects enter into transmitted pattern.

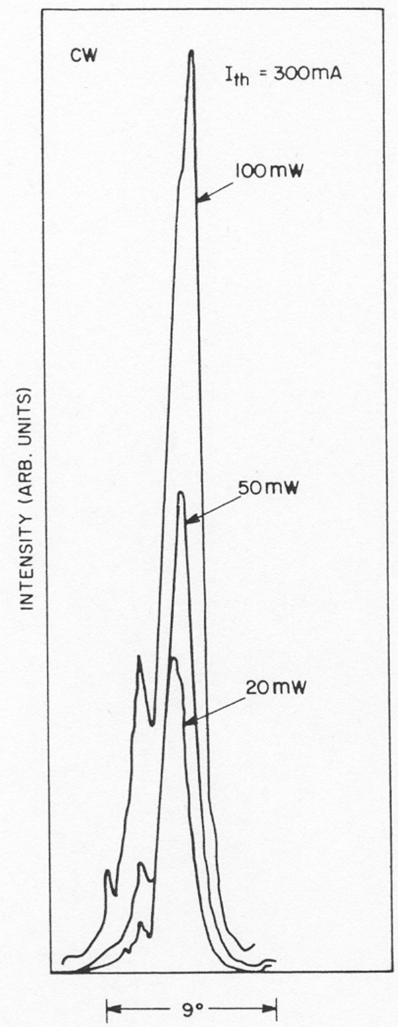
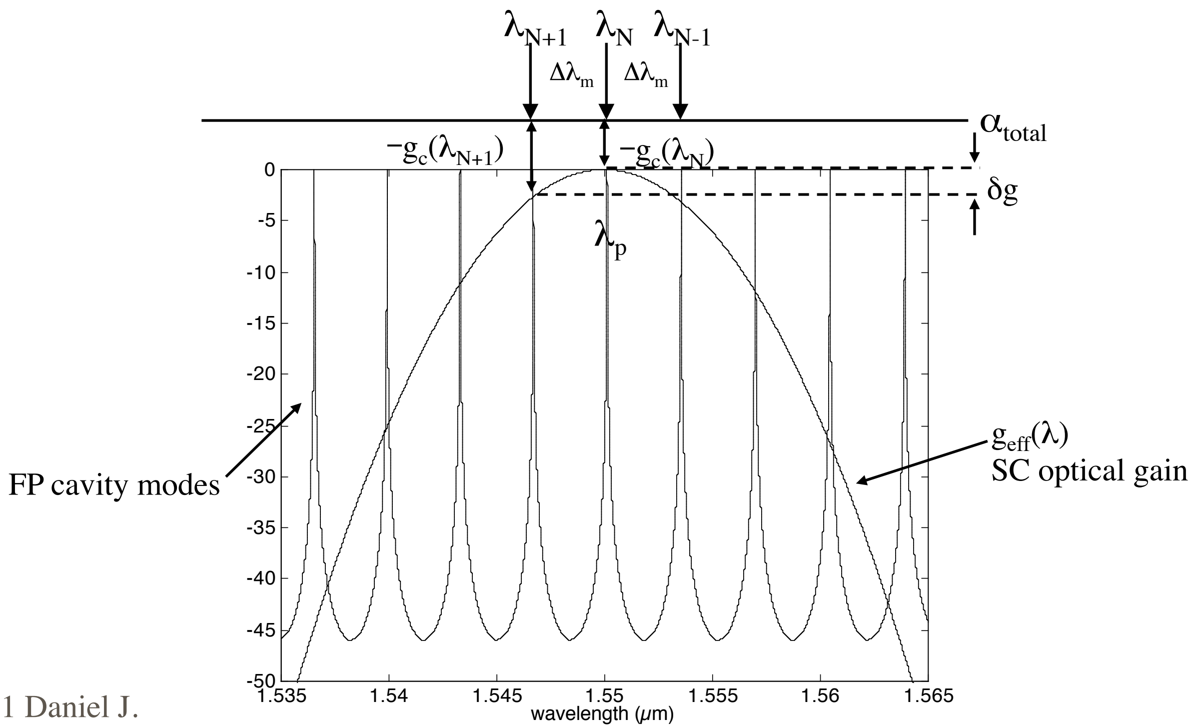


Fig. 5.38 Far fields along the junction plane of a gain-guided 1.3-μm InGaAsP laser with ten emitters showing in-phase operation.

Side Mode Suppression Ratio SMSR

- The output optical spectrum of a laser can contain one or many frequencies
- For high performance communications (2.5Gbps and higher), it is important to use lasers that emit primarily at one frequency (wavelength).
- The SMSR is a standard measure of how single frequency is a laser is
- Consider the following symmetrical model for a semiconductor gain medium embedded in an optical resonator where the gain peak is aligned with one of the resonator modes



Side Mode Suppression Ratio SMSR

- Consider the time-averaged (Stationary) optical power for the dominant mode (N) and second most dominant mode (N+1)

$$\frac{d\overline{S_N}}{dt} = 0 = \Gamma_a \cdot G_N(N) \cdot (1 - \varepsilon \cdot \overline{S_N}) \cdot \overline{S_N} - \frac{\overline{S_N}}{\tau_p} + \frac{\Gamma_a \beta_{sp} N}{\tau_n}$$

$$\frac{d\overline{S_{N+1}}}{dt} = 0 = \Gamma_a \cdot G_{N+1}(N) \cdot (1 - \varepsilon \cdot \overline{S_{N+1}}) \cdot \overline{S_{N+1}} - \frac{\overline{S_{N+1}}}{\tau_p} + \frac{\Gamma_a \beta_{sp} N}{\tau_n}$$

- The SMSR is defined as

$$\text{SMSR} = \frac{\overline{S_N}}{\overline{S_{N+1}}}$$

- For a gain spectrum much larger than the cavity mode spacing, assume there is minimal wavelength dependence to the last term in the rate equations (assuming non-linear gain is zero)

$$\text{SMSR} = \frac{\overline{S_N}}{\overline{S_{N+1}}} = \frac{\Gamma_a \cdot G_{N+1}(N) - \dfrac{1}{\tau_p}}{\Gamma_a \cdot G_N(N) - \dfrac{1}{\tau_p}}$$

Mode Selectivity

- For single mode operation in a digitally modulated laser, numerical simulations of multi-mode rate equations show that the dominant mode gain must exceed gain of all other modes by order 5 cm^{-1}.

$$\Delta g_c = SMSR \frac{n_{sp}}{2} h\nu v_g \alpha_m (\alpha_i + \alpha_m) \frac{1}{P_{off}}$$

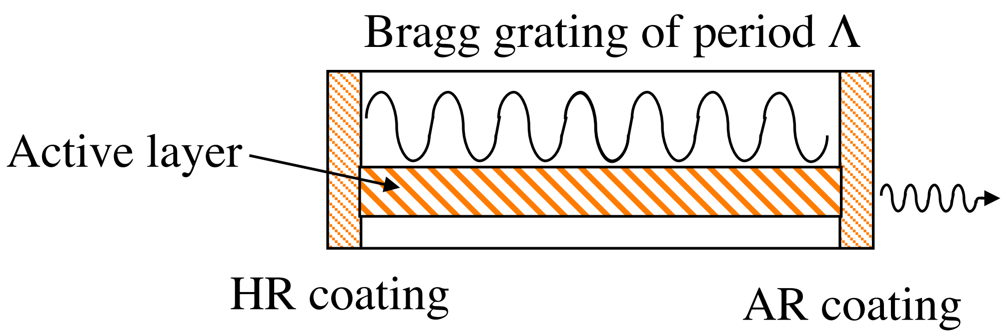
- Where n_{sp} is the spontaneous emission factor, v_g is the mode group velocity and P_{off} is the power in a "zero" bit

- Example: SMSR = 100; n_{sp} = 3; hv = 0.8eV; $v_g = c/n_{eff} = 3x10^8/4$; $\alpha_m = \alpha_i$ = 30 cm^{-1}; P_{off}=0.025mW
  - $\Delta g_c = 10cm^{-1}$

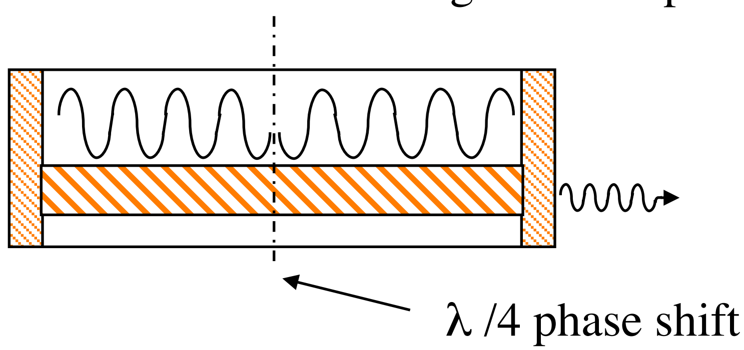
- Note: In practice it is very difficult to get (and keep) the gain peak aligned with a cavity resonance, so the SMSR not only decreases, but the laser can be unstable between two modes that are competing for the gain.

Distributed Feedback (DFB) Lasers

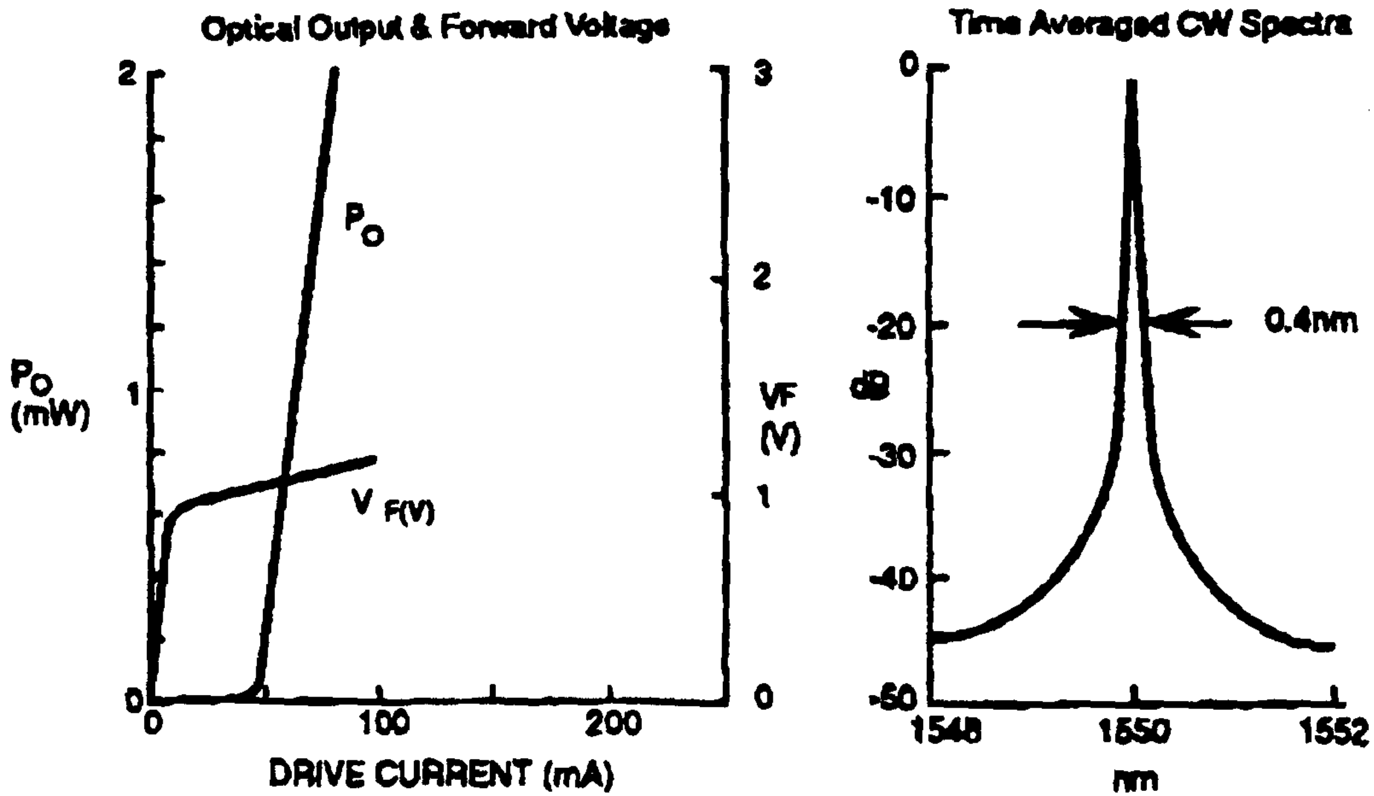
•Embedded optical grating is used to reduce loss for desired lasing mode, and increase loss for undesired modes. Lasing wavelength $\lambda_B = 2\,\Lambda\,n$



⇒But really two modes lase.
⇒ Bragg grating with λ /4 phase shift is used for single mode operation.



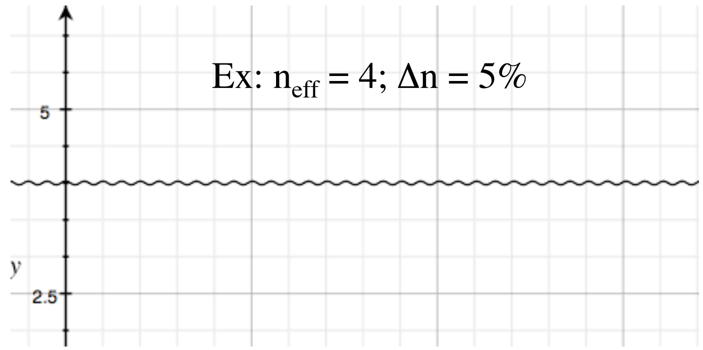
DFB Laser Output Characteristics



Periodic Index Structures

- Many of the SML lasers in use today rely on some form of periodic structure to create a wavelength dependent loss designed to allow only one mode to dominate and a large resulting SMSR
  - Examples include Distributed Bragg Reflector Laser (DBR) and the Distributed Feedback Laser (DFB)
- A periodic structure is defined as where the index of refraction varies periodically in the direction of propagation only

$$n(z) = n'_{eff} + \frac{\Delta n}{2}\cos(2\beta_0 z)$$



- The Bragg period of the structure is defined as $\Lambda = M\pi/\beta_0$, with M an integer. For M=1 (first order structure), the free space Bragg wavelength can be used to describe the Bragg period

$$\Lambda = \frac{\lambda_B}{2n'_{eff}}$$

Periodic Index Structures

- Defining the grating vector (related to the periodic structure) $k_g = 2\pi/\Lambda$ and the coupling coefficient κ, the wave equation for a field with free space propagation constant ($k_0 = 2\pi/\lambda$) propagating in the periodic medium is

$$\frac{d^2E}{dz^2} + \left[n(z)k_0\right]^2 E = \frac{d^2E}{dz^2} + \left[\left(n_{eff}' + \frac{\Delta n}{2}\cos\left(2\beta_0 z\right)\right)k_0\right]^2 E = 0$$

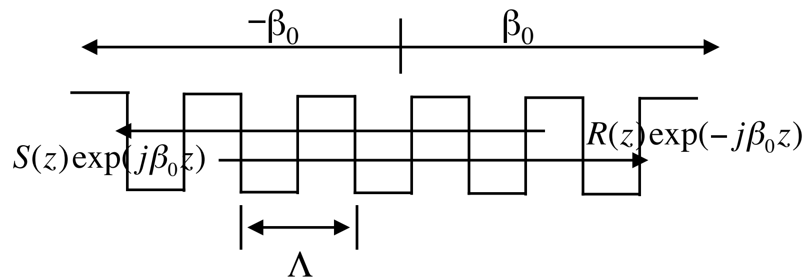
$$\frac{d^2E}{dz^2} + \left[k_0^2\left(n_{eff}^2 + n_{eff}'\Delta n\cos\left(2\beta_0 z\right)\right)\right]E = \frac{d^2E}{dz^2} + \left[\beta^2 + 4\beta\kappa\cos\left(2\beta_0 z\right)\right]E = 0$$

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

- Consider wavelengths λ close to the Bragg wavelength λ_B such that $\beta = \beta_0 + \Delta\beta$ and $\Delta\beta << \beta_0$
- Using the picture below, we describe the forward and backward propagating waves by

$$E(z) = R(z)\exp(-j\beta_0 z) + S(z)\exp(j\beta_0 z)$$

Note: In Yariv, A=R and B=S



Periodic Index Structures (3)

- Inserting the backward and forward propagating field into the wave equation with periodically varying index of refraction

$$\frac{d^2\left[R(z)\exp(-j\beta_0 z)+S(z)\exp(j\beta_0 z)\right]}{dz^2}+\left[\beta^2+4\beta\kappa\cos\left(2\beta_0 z\right)\right]\left[R(z)\exp(-j\beta_0 z)+S(z)\exp(j\beta_0 z)\right]=0$$

$$\frac{d\left[-j\beta_0 R(z)\exp(-j\beta_0 z)+j\beta_0 S(z)\exp(j\beta_0 z)+R'(z)\exp(-j\beta_0 z)+S'(z)\exp(j\beta_0 z)\right]}{dz}+\left[\beta^2+4\beta\kappa\cos\left(2\beta_0 z\right)\right]\left[R(z)\exp(-j\beta_0 z)+S(z)\exp(j\beta_0 z)\right]=0$$

$$-\beta_0^2 R(z)\exp(-j\beta_0 z)-\beta_0^2 S(z)\exp(j\beta_0 z)-j\beta_0 R'(z)\exp(-j\beta_0 z)+j\beta_0 S'(z)\exp(j\beta_0 z)-j\beta_0 R'(z)\exp(-j\beta_0 z)+j\beta_0 S'(z)\exp(j\beta_0 z)+$$
$$\beta^2 R(z)\exp(-j\beta_0 z)+\beta^2 S(z)\exp(j\beta_0 z)+4\beta\kappa\cos\left(2\beta_0 z\right)R(z)\exp(-j\beta_0 z)+4\beta\kappa\cos\left(2\beta_0 z\right)S(z)\exp(j\beta_0 z)=0$$

$$\left(\beta^2-\beta_0^2\right)R(z)\exp(-j\beta_0 z)+\left(\beta^2-\beta_0^2\right)S(z)\exp(j\beta_0 z)-2j\beta_0 R'(z)\exp(-j\beta_0 z)+2j\beta_0 S'(z)\exp(j\beta_0 z)+$$
$$4\beta\kappa\cos\left(2\beta_0 z\right)R(z)\exp(-j\beta_0 z)+4\beta\kappa\cos\left(2\beta_0 z\right)S(z)\exp(j\beta_0 z)=0$$

$$\exp(-j\beta_0 z)\left[\left(\beta^2-\beta_0^2\right)-2j\beta_0 R'(z)+4\beta\kappa\cos\left(2\beta_0 z\right)R(z)\right]+\exp(j\beta_0 z)\left[\left(\beta^2-\beta_0^2\right)+2j\beta_0 S'(z)+4\beta\kappa\cos\left(2\beta_0 z\right)S(z)\right]=0$$

$$\beta^2=\beta_0^2+\Delta\beta^2+2\beta_0\Delta\beta\cong\beta_0^2+2\beta_0\Delta\beta$$

$$\exp(-j\beta_0 z)\left[2\beta_0\Delta\beta-2j\beta_0 R'(z)+4\beta\kappa\cos\left(2\beta_0 z\right)R(z)\right]+\exp(j\beta_0 z)\left[2\beta_0\Delta\beta+2j\beta_0 S'(z)+4\beta\kappa\cos\left(2\beta_0 z\right)S(z)\right]=0$$

- Which can be described by the coupled-mode equations

$$R'(z)+j\Delta\beta R(z)=-j\kappa S(z)$$
$$S'(z)-j\Delta\beta S(z)=j\kappa R(z)$$

Distributed Bragg Reflector (DBR) Lasers

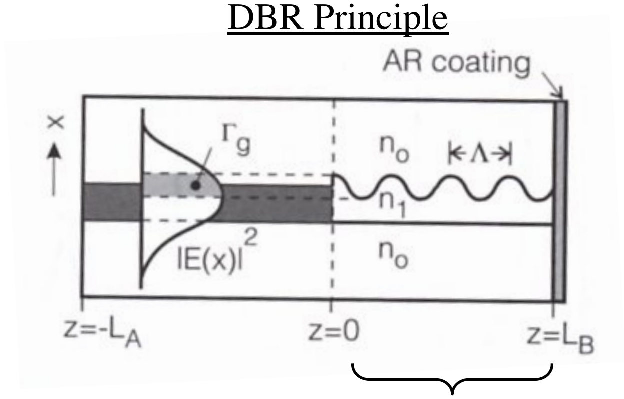
- Bragg reflector acts as wavelength dependent mirror
- Long gratings and weak coupling coefficient realizes a mirror with high reflectivity and narrow reflection peak (spectrum)
- The gain condition and net modal gain can be written as

$$R_1 R_{per} \exp(2 g_{net} L_A) = 1$$

$$g_{net} = \frac{1}{2L_A}\left[\ln\frac{1}{R_1} + \ln\frac{1}{R_{per}}\right]$$

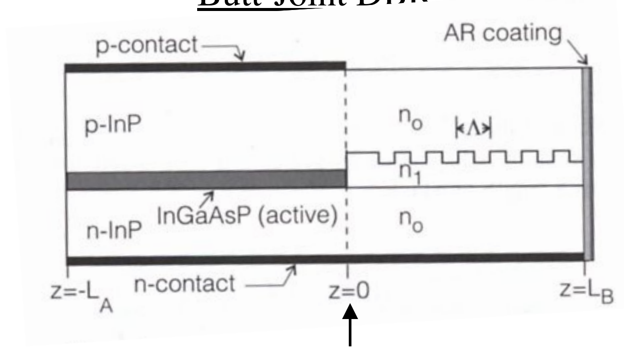
Power that leaves active region at z=0

DBR Principle



Bragg Grating = wavelength dependent mirror

Butt-Joint DBR



Lasing quality depends strongly on quality of interface

Distributed Bragg Reflector (DBR) Lasers

- To understand how the reflectivity varies as the wavelength shifts away from the Bragg wavelength, we introduce the normalized parameter

$$\Delta\beta = \beta - \beta_0 = \frac{2\pi n'_{eff}(\lambda)}{\lambda} - \frac{2\pi n'_{eff}(\lambda_B)}{\lambda_B} \approx \frac{2\pi n_g}{\lambda_B^2}\Delta\lambda$$

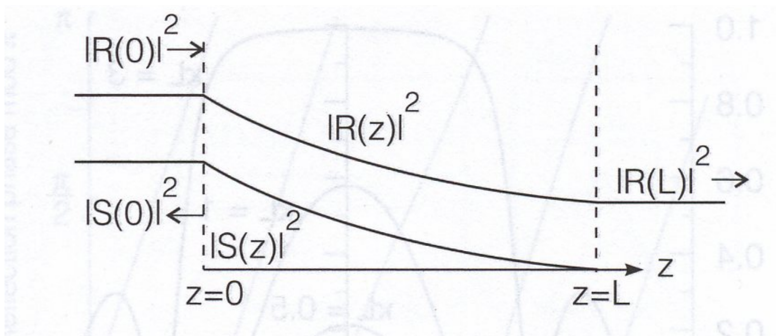
$$n_g = \left.\frac{d\left(k_0 n'_{eff}\right)}{dk_0}\right|_{\lambda_N}$$

- At wavelengths near the Bragg wavelength, a periodic structure of length L, and an incoming field of magnitude R(0) at z=0 and S(L) = 0 at z=L

$$R(z) = \frac{\cosh\left(\kappa\left(z-L\right)\right)}{\cosh\left(\kappa L\right)}R(0)$$

$$S(L) = \frac{j\sinh\left(\kappa\left(z-L\right)\right)}{\cosh\left(\kappa L\right)}R(0)$$

$$\left|R(z)\right|^2 - \left|S(z)\right|^2 = \left|R(L)\right|^2$$

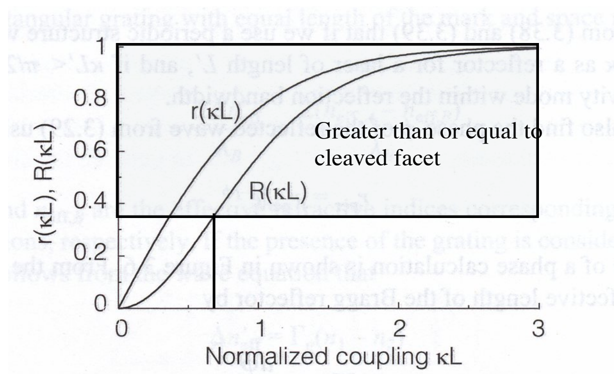


Distributed Bragg Reflector (DBR) Lasers

- At the Bragg wavelength, $\Delta\beta=0$, which means $\gamma = \kappa$, and the reflectivity only depends on κL

$$\left|r_{per}\right| = \left|\frac{S(0)}{R(0)}\right| = \left|\frac{-j\sinh(\kappa L)}{\cosh(\kappa L)}\right| = \tanh(\kappa L)$$

$$R_{per} = \left|r_{per}\right|^2 = \tanh^2(\kappa L)$$

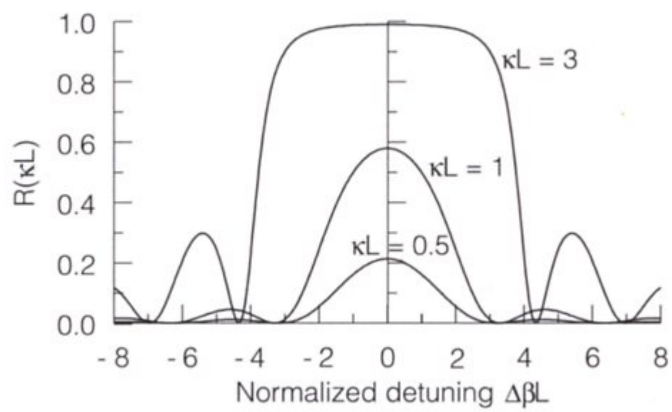


- If we now look at the reflectivity as a function of wavelength offset from the Bragg wavelength as a parameter of κL. The reflectivity function is periodic with nulls at (assuming $\Delta\beta L > \kappa L$)

$$\Delta\beta L = \sqrt{(\kappa L)^2 + (N\pi)^2}\text{, for } N = 1,2,\ldots,$$

- The reflection bandwidth for the Bragg mirror is

$$\Delta\lambda_r = \frac{\lambda_B^2\kappa}{\pi n_{g,eff}} = \frac{\lambda_B \Delta n}{2 n_{g,eff}}$$



Distributed Bragg Reflector (DBR) Lasers

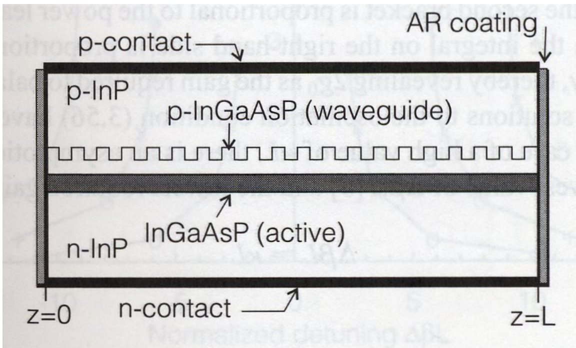
- Recall that in this design the Bragg mirror is only one of the mirrors. The other mirror is a broadband FP type mirror. There are designs where a Bragg mirror is used for both mirrors.
- A key question is then, how many FP modes are there within the primary reflection mode of the Bragg mirror? If there is more than one, then we will not have a single mode laser
- Lets plug in the coupling coefficient into the standard mode spacing equation for a FP laser
- Single mode operation occurs when only one cavity mode fits under the Bragg reflector bandwidth, or

$$\Delta\lambda_m = \frac{\lambda^2}{2n_{g,eff}L} > \frac{\lambda_B^2\kappa}{\pi n_{g,eff}} = \Delta\lambda_r$$

$$\kappa L < \pi/2$$

Distributed Feedback (DFB) Lasers

- DFB lasers employ Bragg mirrors. The mirror is "distributed" through the laser gain medium instead of at the ends like with DBR lasers.
- First consider the case of a DFB laser with non-reflecting facets (e.g. semiconductor facets are highly AR coated)



- To allow for the presence of gain, we need to modify $\Delta\beta$ with $\Delta\beta + jg_0$. In this example there are no mirrors, so the matrix F_{per} describes the fields and the oscillation condition for lasing is $(F_{per})_{22} = 0$.

$$F_{per} = \begin{pmatrix} \left[\cosh(\gamma L) - \frac{j\Delta\beta}{\gamma}\sinh(\gamma L)\right] & -\frac{j\kappa}{\gamma}\sinh(\gamma L) \\ \frac{j\kappa}{\gamma}\sinh(\gamma L) & \left[\cosh(\gamma L) + \frac{j\Delta\beta}{\gamma}\sinh(\gamma L)\right] \end{pmatrix}$$

$$\left(F_{per}\right)_{22} = 0$$

$$\cosh(\gamma L) + \frac{j\left(\Delta\beta + jg_0\right)}{\gamma}\sinh(\gamma L) = 0$$

Distributed Feedback (DFB) Lasers

- The wave equation sets the relation between gain and the distributed mirror parameters as

$$\gamma^2 = \kappa^2 - (\Delta\beta + jg_0)^2$$

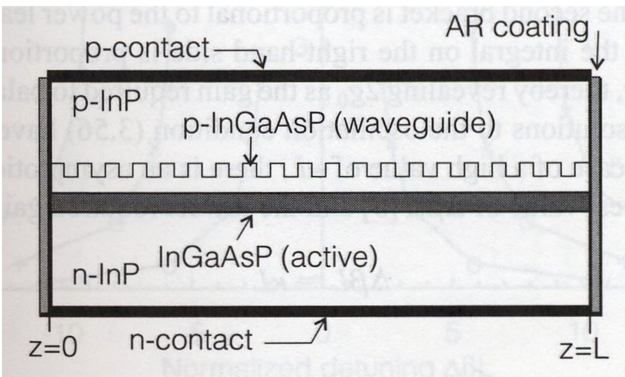
- And the oscillation condition can be written as

$$\gamma L \coth(\gamma L) = -j(\Delta\beta L + jg_0 L)$$

- The gain and phase for the DFB are tightly coupled in contrast to the FP laser. The complex number in the above equation determines the gain and phase. The coupling coefficient and length together determine the possible values for $\Delta\beta L$ and $g_0 L$. The oscillation condition will yield a set of solutions, each with a wavelength (given by $\Delta\beta$) and gain for that wavelength (given by g_0).

Distributed Feedback (DFB) Lasers

- Last lecture we talked about uncoated DFB lasers, where the structure could be treated as a periodic matrix modified to include gain ($\Delta\beta + jg_0$), and setting $(F_{per})_{22} = 0$. The oscillation condition is repeated below



$$F_{per} = \begin{pmatrix} \left[\cosh(\gamma L) - \frac{j\Delta\beta}{\gamma}\sinh(\gamma L)\right] & -\frac{j\kappa}{\gamma}\sinh(\gamma L) \\ \frac{j\kappa}{\gamma}\sinh(\gamma L) & \left[\cosh(\gamma L) + \frac{j\Delta\beta}{\gamma}\sinh(\gamma L)\right] \end{pmatrix}$$

$$\left(F_{per}\right)_{22} = 0$$

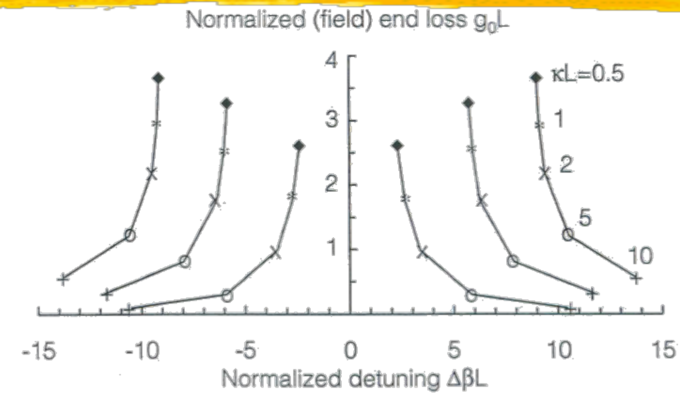
$$\text{Oscillation Condition:} \gamma L \coth(\gamma L) = -j\left(\Delta\beta L + jg_0 L\right) = 0$$

- To understand how power is emitted from this structure consider the following energy conservation relation

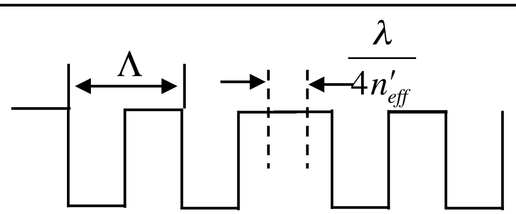
$$\underbrace{\left[\left|R(L)^2\right| - \left|S(L)^2\right|\right]}_{\text{~Power leaving right end of DFB}} + \underbrace{\left[\left|S(0)^2\right| - \left|R(0)^2\right|\right]}_{\text{~Power leaving left end of DFB}} = \underbrace{2g_0\int_0^L \left[\left|R(z)^2\right| + \left|S(z)^2\right|\right]dz}_{\text{~Energy stored in DFB cavity}}$$

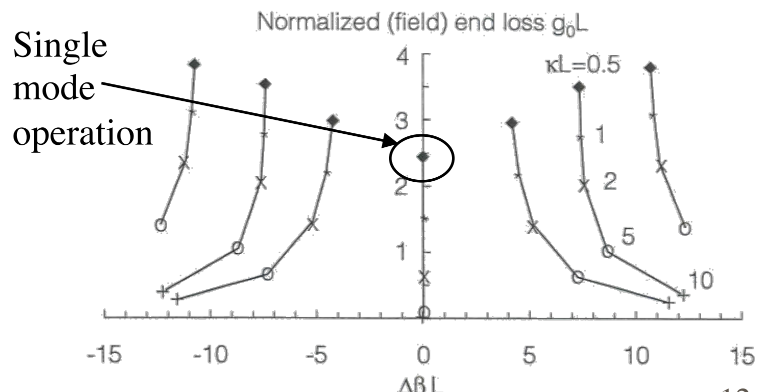
Distributed Feedback (DFB) Lasers

- Using the oscillation condition to solve numerically for g_0L as a function of normalized detuning $\Delta\beta L$ parameterized as a function of κL, we see in the figure on the right
  - Increased feedback (κL) results in lower required gain (g_0L)
- There is an inherent symmetry in the cavity, solutions for both $\Delta\beta L$ and - $\Delta\beta L$
  - ***Means that the DFB is inherently a two mode (not single mode) laser!***



- To make a single mode DFB laser there are some design changes we can leverage
- AR coat one facet and leave the other facet cleaved.
  - Provides mode selectivity by matching only a subset of distributed mirror reflection (modes) with phase of end mirror. But this can itself be unstable and random.
- Phase shifted distributed Bragg grating.
  - Places a mode at the Bragg wavelength AND it is the lowest loss mode.

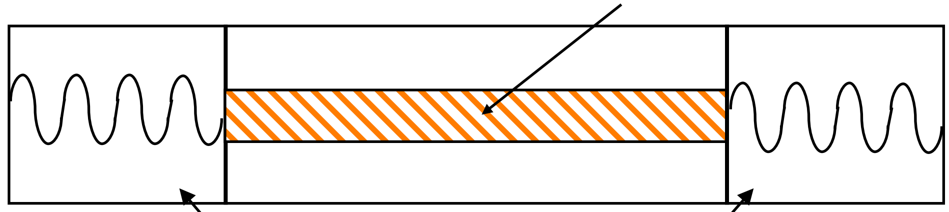




Distributed Bragg Reflector (DBR) Lasers

- Similar structure as DFB
- Bragg gratings are used as wavelength dependent mirrors.

Active Region



R(λ)

R(λ)

Bragg grating reflectors (passive waveguides)

$\lambda = 2\,\Lambda\, n$

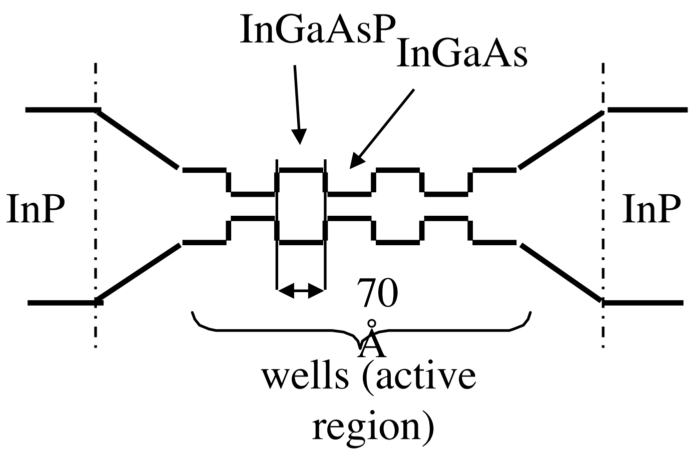
Mode index of refraction

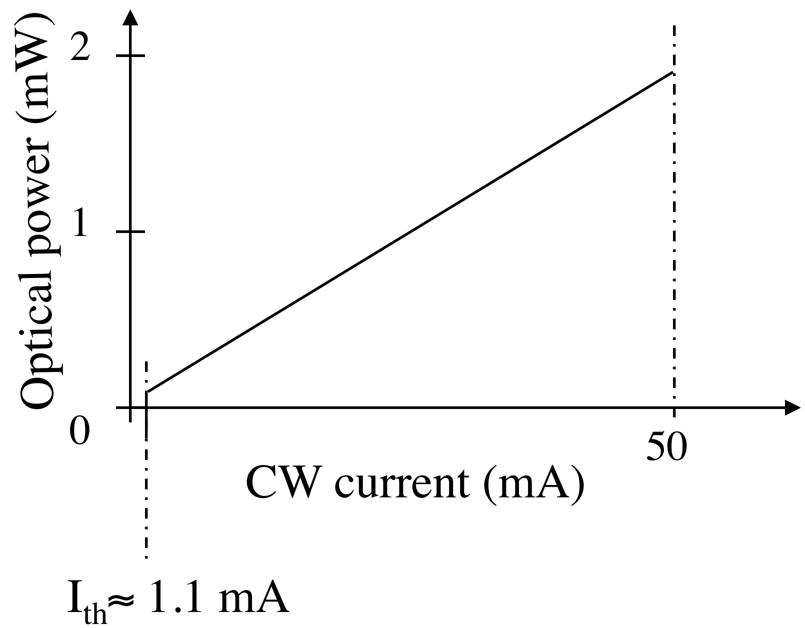
Quantum well lasers

• Lower threshold current, higher efficiency, higher modulation bandwidth, lower spectral width

•Less temperature dependence on wavelength and threshold current.

•Lower linewidth broadening during modulation.





Quantum Well Wavefunctions

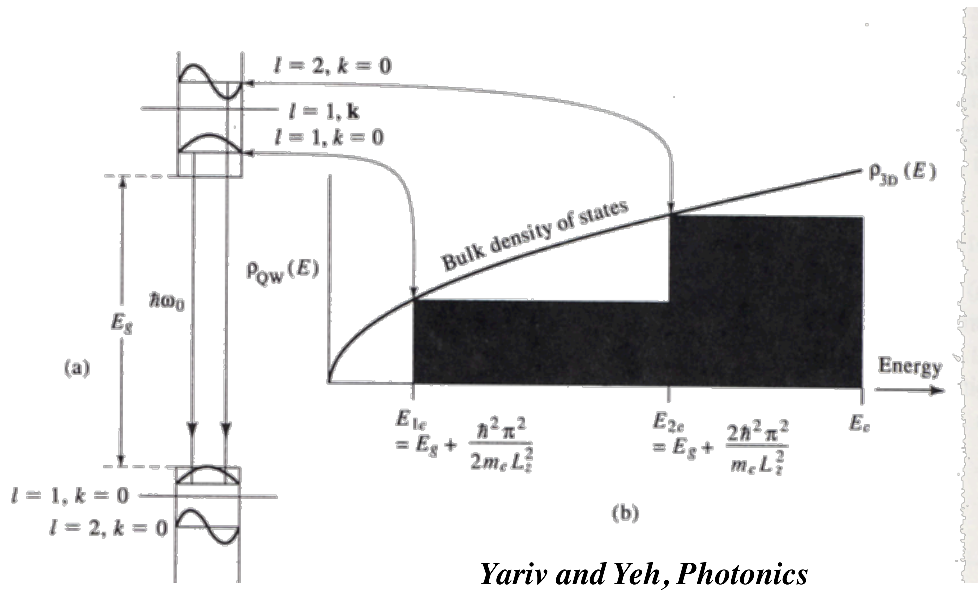
• The complete wavefunctions for electrons in the conduction band and holes in the valance band are given by, and are shown in the figure below.

$$\psi_c(r) = \sqrt{\frac{2}{L_z}}\psi_{k\perp c}(r_\perp)CS\left(l\frac{\pi}{L_z}z\right)$$

$$\psi_v(r) = \sqrt{\frac{2}{L_z}}\psi_{k\perp v}(r_\perp)CS\left(l\frac{\pi}{L_z}z\right)$$

$$\psi_c(r)_{groundstate} = \sqrt{\frac{2}{L_z}}\psi_{k\perp c}(r_\perp)Cos\left(\frac{\pi}{L_z}z\right)$$

$$\psi_v(r)_{groundstate} = \sqrt{\frac{2}{L_z}}\psi_{k\perp v}(r_\perp)Cos\left(\frac{\pi}{L_z}z\right)$$



Yariv and Yeh, Photonics

Density of States

• Assuming the electrons are confined to rectangles with L_x and L_y much larger than L_z, the K vectors are quantized according to

$$k_x = n\frac{\pi}{L_x}, n = 1,2,\ldots$$

$$k_y = m\frac{\pi}{L_x}, m = 1,2,\ldots$$

• The area in k space per eigenstate is $A_{state}=\pi^{2/} L_xL_y$, and the number of states as a function of k is $N(k)=k^2 L_xL_y/2\pi$

• The νumber of states between k and k+dk and the number of states with energies between E and E+dE are given by

$$\rho(k)dk = \frac{dN(k)}{dk} = L_xL_y\frac{k}{\pi}dk$$

$$\frac{dN(E)}{dE}dE = \frac{dN(k)}{dk}\frac{dk}{dE} = L_xL_y\frac{k}{\pi}dk$$

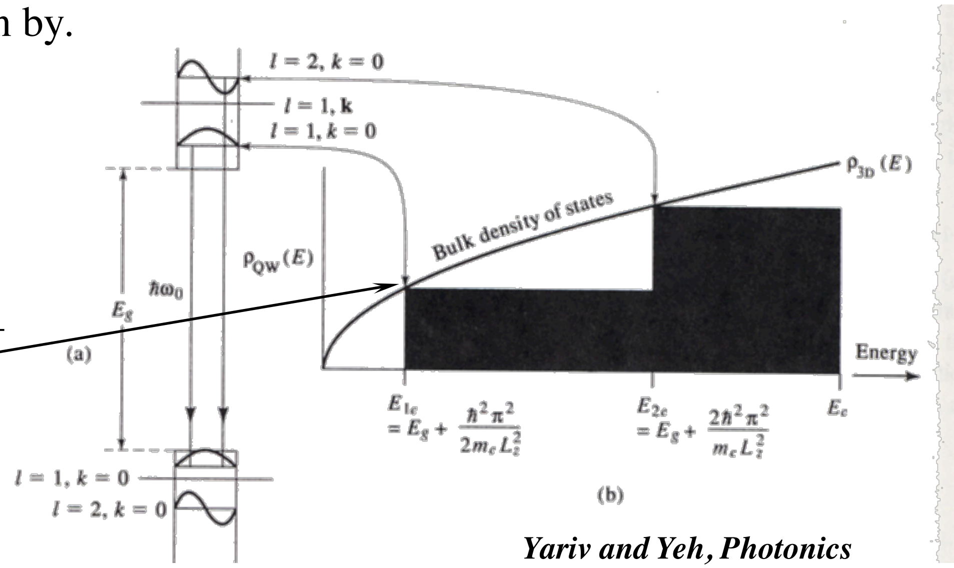
QW Gain Medium Density of States

• If we consider the lowest energy state in the conduction band, where electrons are free to move in 2D and confined in the third dimension by the well, the density of states per unit energy per unit area is constant and is given by.

$$\rho_{QW}(E) = \frac{1}{A_\perp}\frac{dN(E)}{dE} = \frac{k}{\pi}\frac{dk}{dE}$$

$$= \frac{1}{\pi}\sqrt{\frac{2m_c}{\hbar^2}}\left(E - E_{1c}\right)^{1/2} \frac{d\left(\sqrt{\frac{2m_c}{\hbar^2}}\left(E - E_{1c}\right)^{1/2}\right)}{dE}$$

$$= \frac{m_c}{\pi\hbar^2}$$



Yariv and Yeh, Photonics

• If the well can support the two lowest energy states (E_{1c} and E_{2c}) then the density of states doubles, and if it supports (E_{1c}, E_{2c} and E_{3c}) the density of states triples and so on leading to a staircase function shown above and given by (where H(x) is the Heaviside function = 1, x>0 and = 0, x<0)

$$\rho_{QW}(E) = \sum_{n=1}^{\text{all states}} \frac{m_c}{\pi\hbar^2} H(E - E_{nc})$$

Gain in QW Lasers

• The highest probability of stimulated recombination of and e-h pair via a photon is from l=1 in the conduction band to l=1 in the valence band. Therefore the highest optical gain will occur between these two levels.

• The l=1 electron state in the conduction band and l=1 hole state in the valence band must have the same l and k values, therefore, the transition energy can be written as

$$\begin{aligned}\hbar\omega &= E_c - E_v \\ &= E_g + E_c(k,l) + E_v(k,l) \\ &= E_g + \left(\frac{1}{m_c} + \frac{1}{m_v}\right)\frac{\hbar^2}{2}\left(k^2 + l^2\frac{\pi^2}{L_z^2}\right) \\ &= E_g + \frac{\hbar^2}{2m_r}\left(k^2 + l^2\frac{\pi^2}{L_z^2}\right)\end{aligned}$$

Gain in QW Lasers

• Using the quantum well carrier density $\rho_{QW}(k) \big/ L_z$ the effective inverted population density due to carriers between *k* and *k*+*dk* is given by

$$N_2 - N_1 \rightarrow \frac{kdk}{\pi L_z}\left[f_c(E_c) - f_v(E_v) \right]$$

• The gain due to electrons within dk and a single sub-band (e.g. *l*=1) can be written as a function of w assuming T_2 is the coherence collision time of an electron and τ the electron-hole recombination lifetime

$$\gamma(\omega_0)\Big|_{l=1} = \frac{m_r \lambda_0^2}{4\pi\hbar L_z n^2 \tau} \int_0^\infty \left[f_c(\hbar\omega) - f_v(\hbar\omega) \right] \frac{T_2}{\pi\left[1 + (\omega - \omega_0)^2 T_2^2\right]}$$

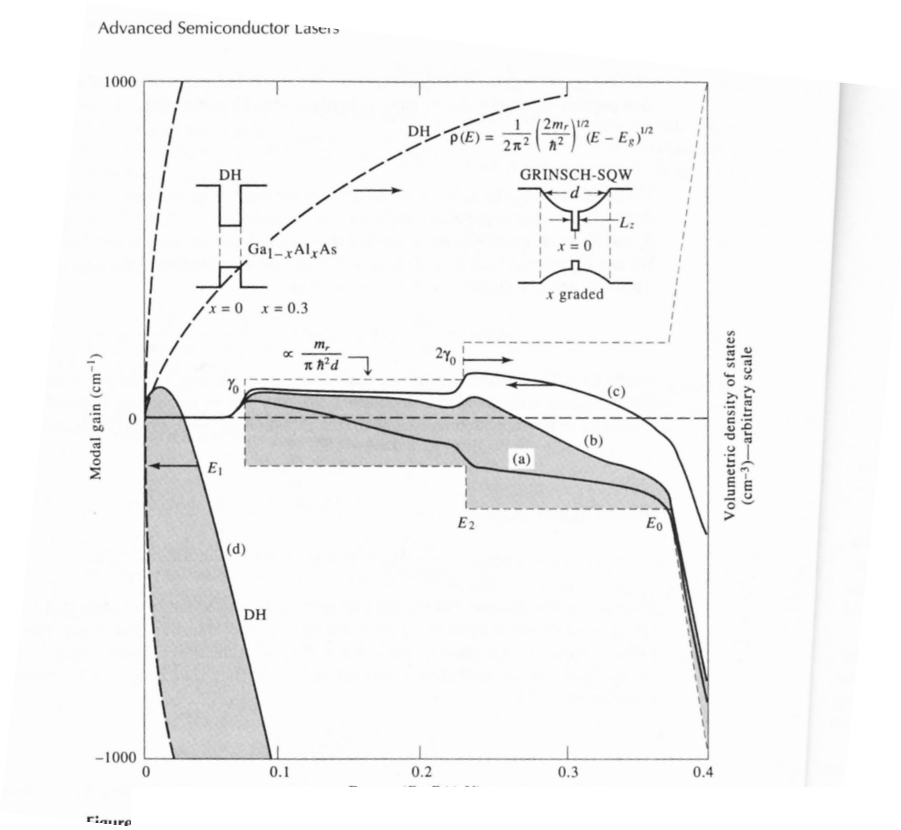
• Including the contributions from all sub-bands we assume

$$\frac{m_r}{\pi\hbar^2} \rightarrow \frac{m_r}{\pi\hbar^2} \sum_{l=1}^{\infty} H(\omega - \omega_l)$$

$$\frac{T_2}{\pi\left[1 + (\omega - \omega_0)^2 T_2^2\right]} \rightarrow \delta(\omega - \omega_0)$$

$$\gamma(\omega_0) = \frac{m_r \lambda_0^2}{4\pi\hbar L_z n^2 \tau}\left[f_c(\hbar\omega_0) - f_v(\hbar\omega_0) \right] \sum_{l=1}^{\infty} H(\hbar\omega_0 - \hbar\omega_l)$$

Gain in QW Lasers



Yariv and Yeh, Photonics

Tunable lasers

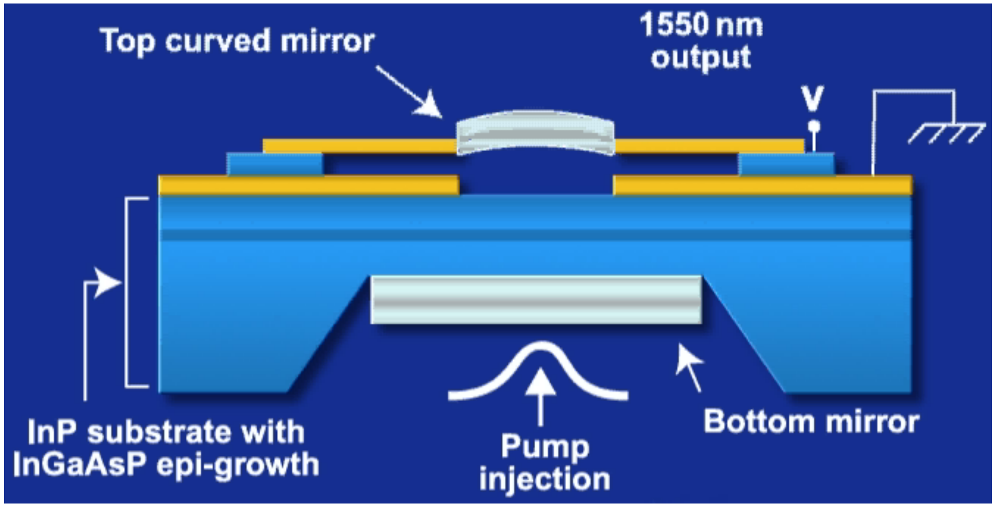
- Several network applications would require fast-tunable lasers
  - Protection application
  - Wavelength conversion
  - Packet switching
- These devices should ideally:
  - Allow to change their output frequency in a very short amount of time (ranging from milliseconds down to nanoseconds, depending on the applications)
  - Be very stable when not switched (just as a DFB laser)
  - Have a wide tuning range (up to several tens of nm)
- Basic principle of operation
  - The filtering function of one of the section of a DBR laser is changed by proper current injection
- Two basic types of tunable laser on the market
  - External cavity diode lasers (ECDLs)
  - Multisection semiconductor lasers

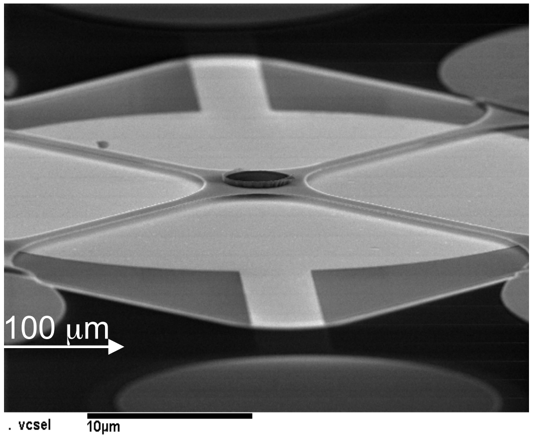
Example Commercially Available Units

- ECDLs
  - New Focus
  - Nortel/Coretek
  - Ioλon
- Multi-Section Semiconductor
  - Agility Communications
  - Agere
  - Altitun/ADC

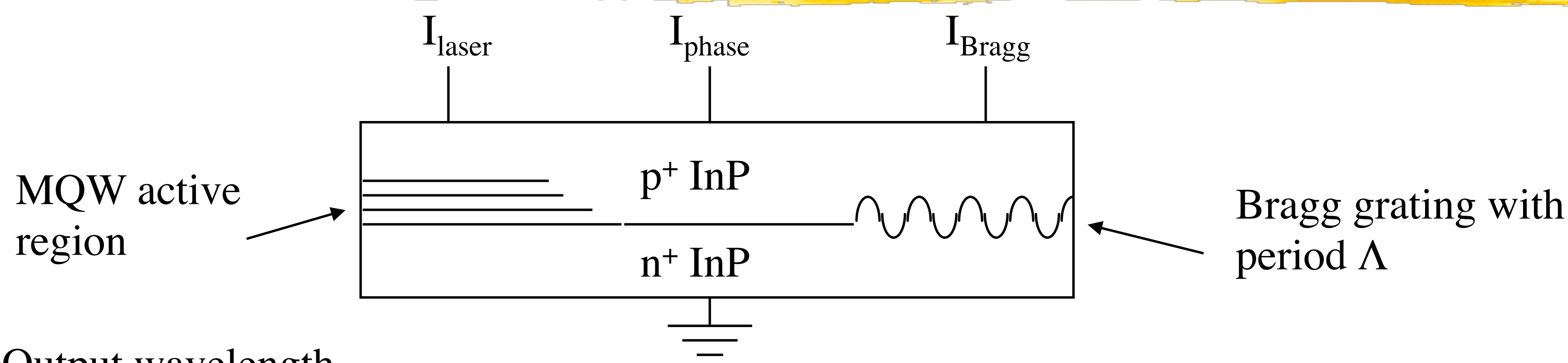
External Cavity Example: MEMS/ VCSEL (Nortel/Coretek)

- Component Technologies
  - InP Laser
  - MEMS
  - Thin Film
  - Packaging
  - High Power (10-20mW)
  - Wide Tuning Range (1/2 to Full Band)
  - Continuously Tunable



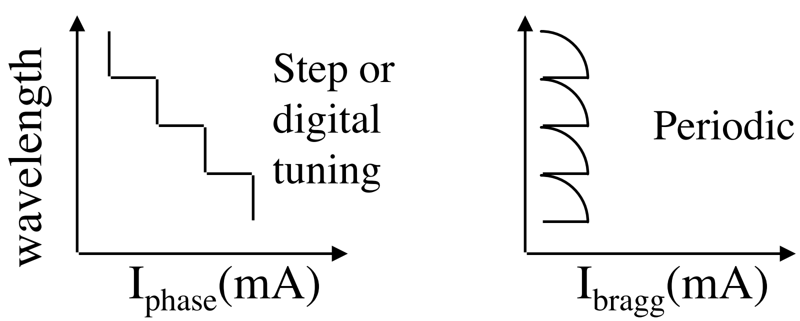


Multisection Wavelength tunable Lasers



- Output wavelength
  - Coarse tuning : $\lambda = 2\bar{\mu}\Lambda$

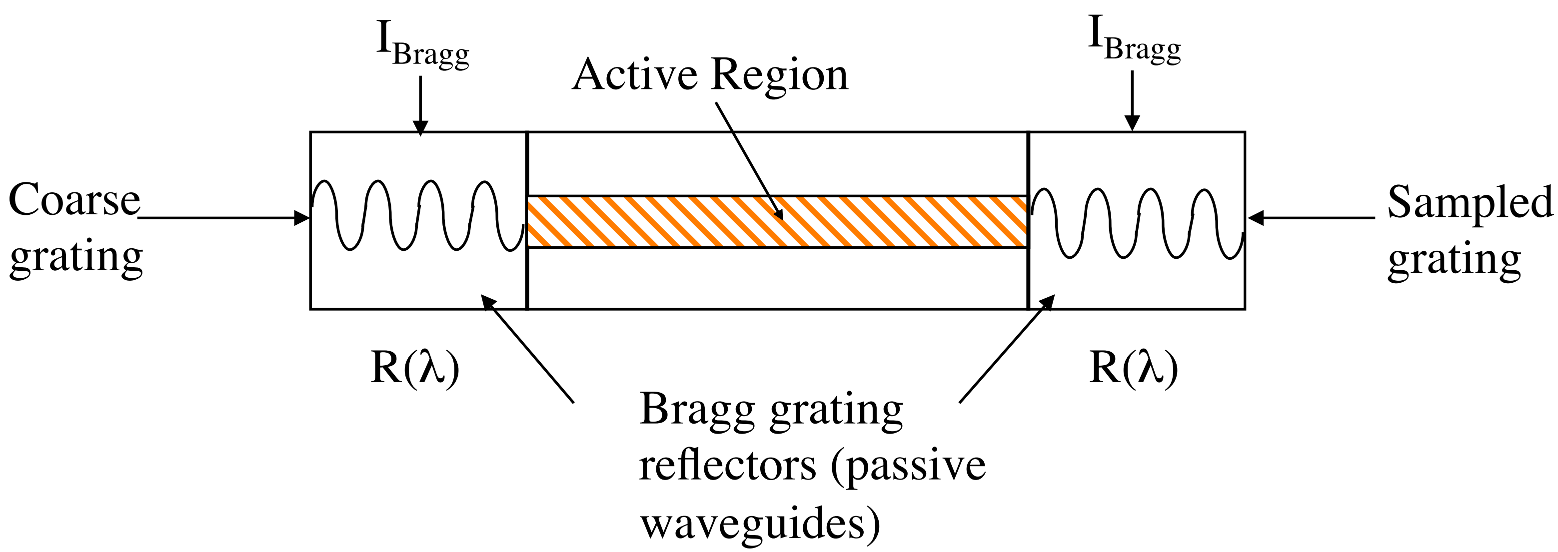
    where $\bar{\mu}$ is the refractive index that can be changed with current ($\bar{\mu}$ (I_{bragg})
  - Fine tuning : Current injection into phase section
- Tunability is on the order of 6 nm



(coarse tuning) + (fine tuning)
= (continuous tuning)

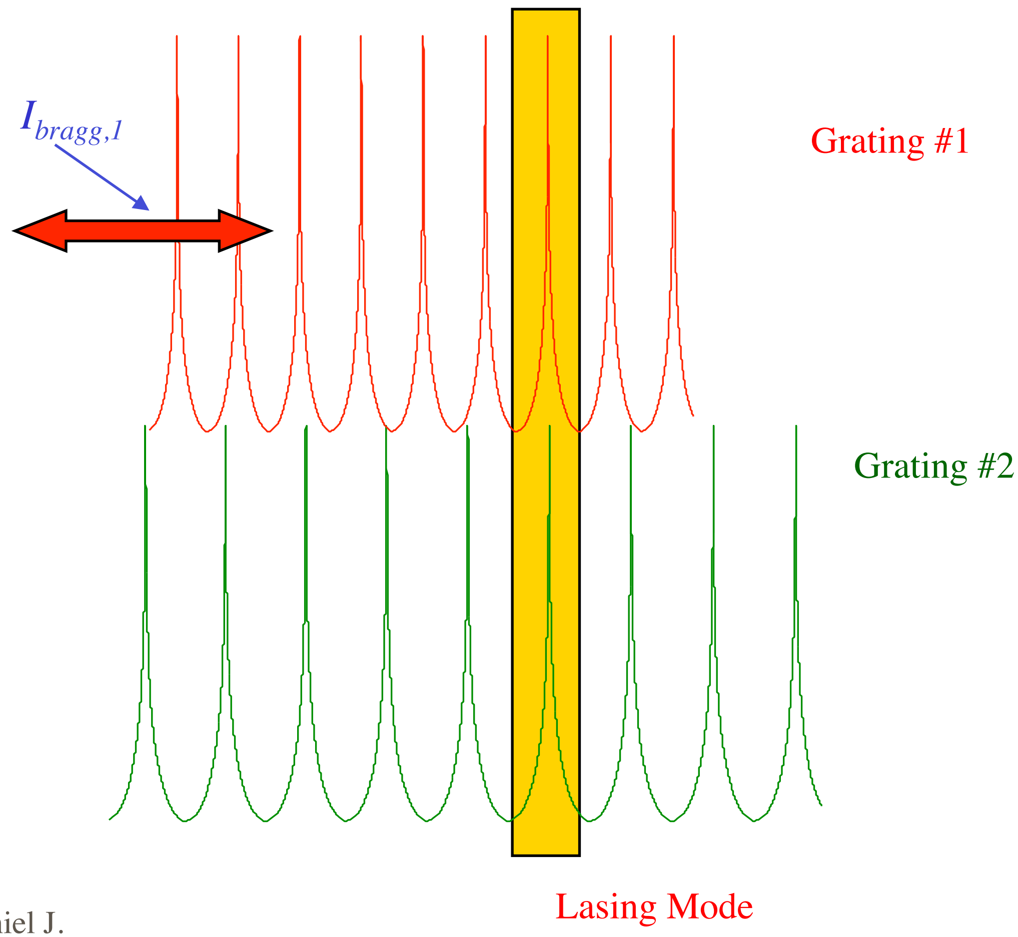
Sampled Grating Tunable Lasers

3-section



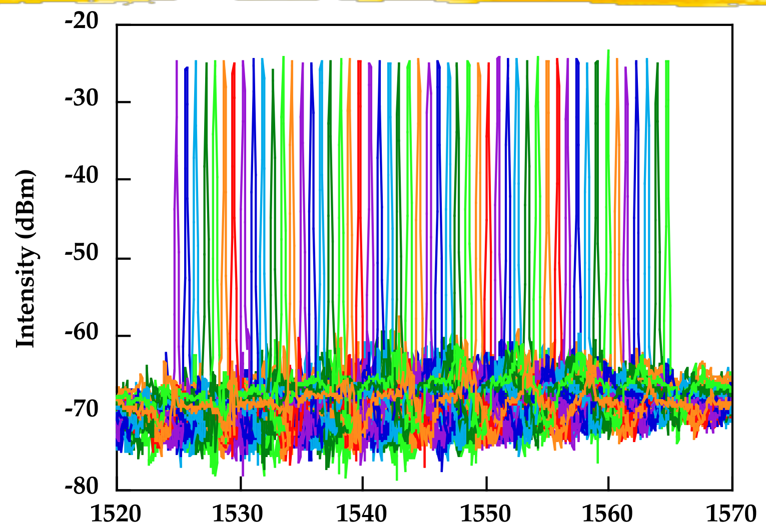
Operates on principle of vernier effect. Each sampled grating has a different mode spacing.

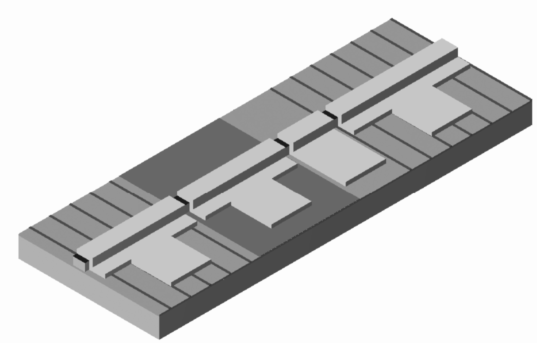
Sampled grating laser – Vernier effect



SGDBR Lasers

- Wavelength accuracy
- Wavelength stability
- Power dependence
- Tuning continuity (mode hopping)
- Side mode suppression ratio (SMSR)
- Tuning range
- Tuning resolution
- Tuning speed (including settling time)
- RIN



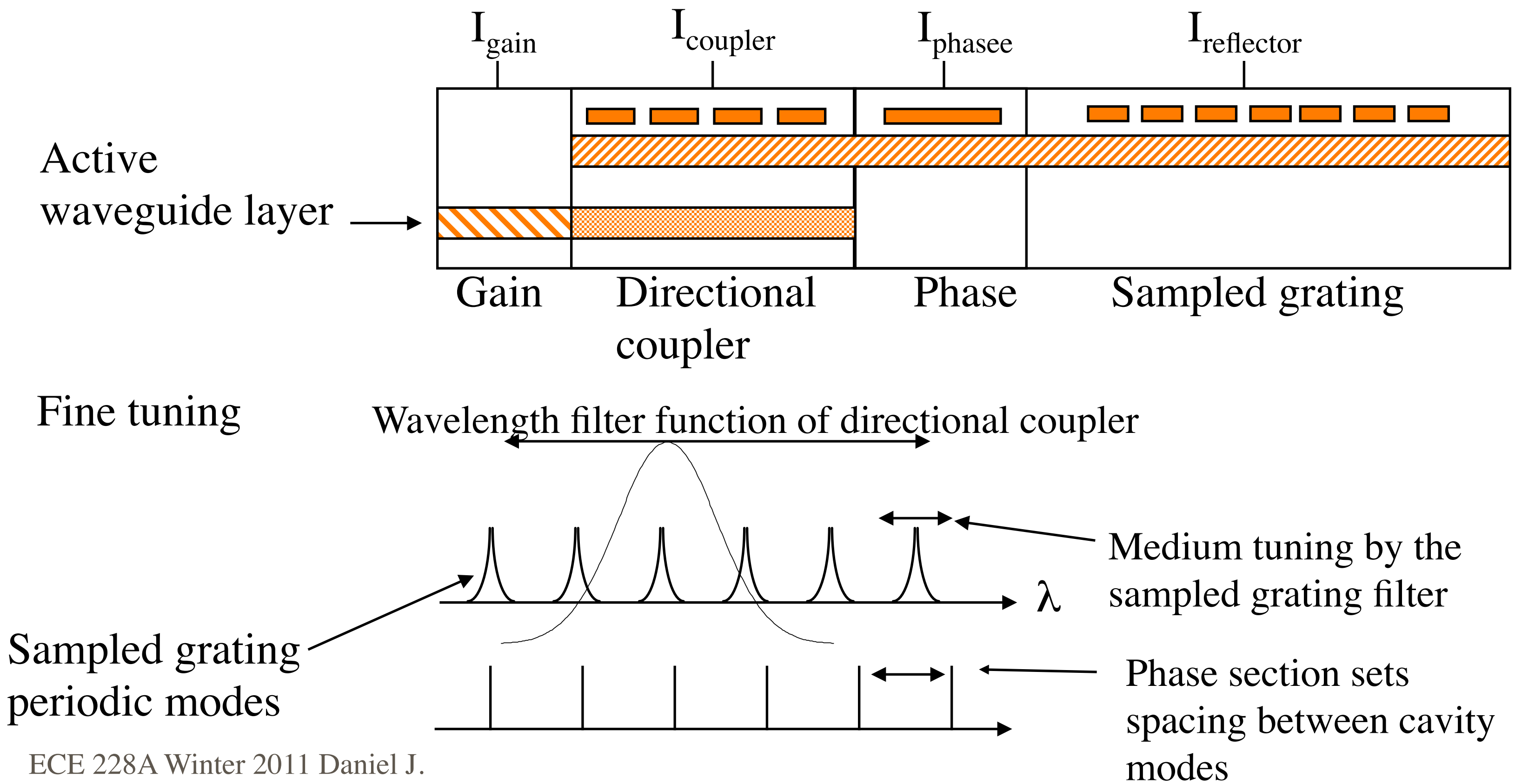


Tunable laser

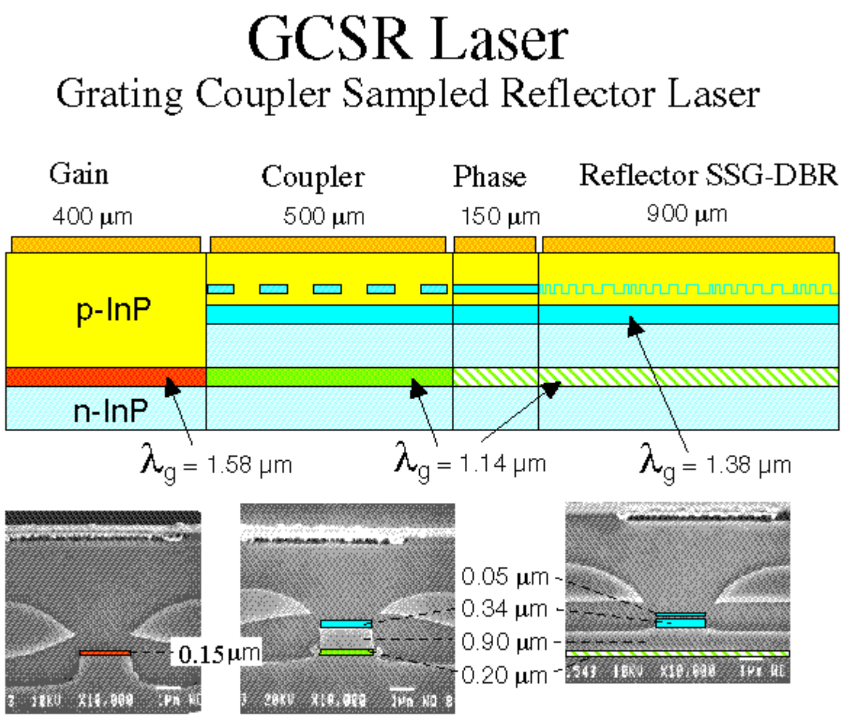
Larry A. Coldren, UCSB, Agility

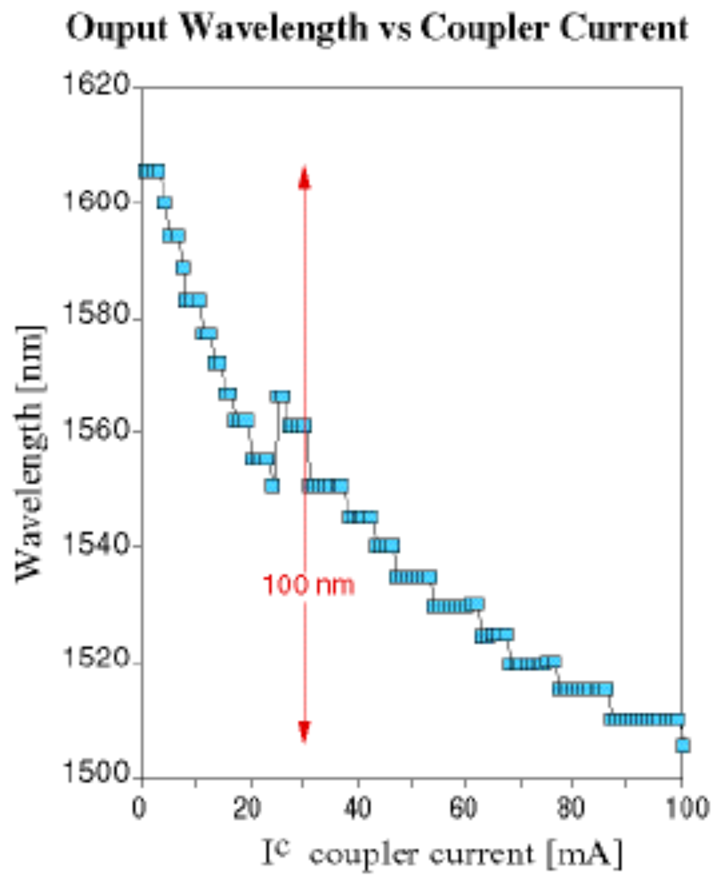
Grating Coupled Sampled Reflector (GCSR)

- <u>4 -section GCSR Laser</u> >100 nm tunability



GCSR Laser Tuning Characteristics





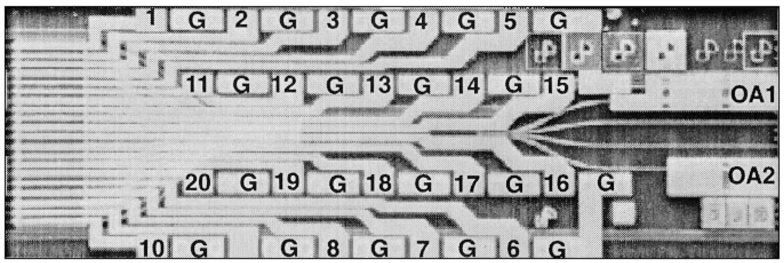
P.-J. Rigole, S. Nilsson, T. Klinga, L. Bäckbom, B. Stalnacke, E. Berglind, B. Stoltz, D. J. Blumenthal, and M. Shell, "Wavelength Coverage Over 67nm with a GCSR Laser Tuning Characteristics and Switching Speed," *Technical Digest of the Optical Fiber Communication Conference (OFC '97)*, Dallas, TX, Paper WL63, February (1997).

Tunable laser - Summary

- Tunable laser are today commercially available
  - The most promising structure seems to be the GCSR one
  - The tuning speed of the laser chip is theoretically really fast (tens of nanoseconds)
  - If high wavelength stability is required, thermal problems have to be controlled accurately
- Consequently:
  - Commercial solutions are available for switching time of the order of milliseconds
  - Setups for nanosecond switching are still at the R&D level

Laser Arrays

20 DFB Lasers



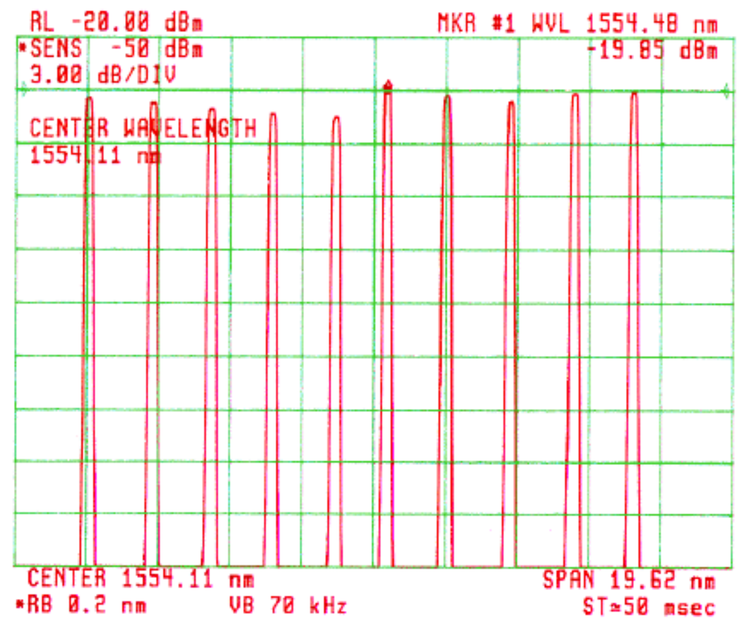
P1
P2

20 x 4 Combiner

SOAs

4.3mm X 1.5mm

Photo by Bellcore



* 10 wavelengths @ 1.65nm spacing, each with a redundant laser
* MONET wavelength compatibility
* 2.5 Gbps operation (25 Gbps aggregate)
* two on-board SOAs
* on chip optical power combiner

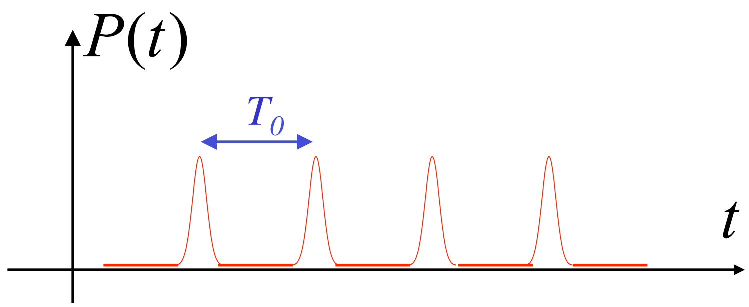
C. E. Zah et. al., Electronics Letters, Vol.. 28, No. 25, pp.. 2361-2362, Dec 3, 1992.

Pulsed Lasers: Motivation

- So far we have studied lasers that emit continuous wave (CW) output power, and studied some aspects of small signal and large signal modulation dynamics.
- In this lecture, we will study a class of laser that emits pulses, or pulse trains, that can be further encoded with data using an external modulator. We will be studying modulators later in the class.
- The following types of lasers that emit pulses are of interest
  - Gain Switched: Directly turning on and off gain of the laser
  - Q-Switched: Periodically increasing the resonator loss (spoiling the Q) with an absorber in the laser cavity
  - Cavity Dumping: Storing photons in the resonator during the off-times and releasing the photons during the on-times.
  - Mode-Locked: Coupling and locking the phases of the cavity modes to each other.
- In this lecture we will talk briefly about gain switched and then concentrate on mode-locked lasers

Pulsed laser sources

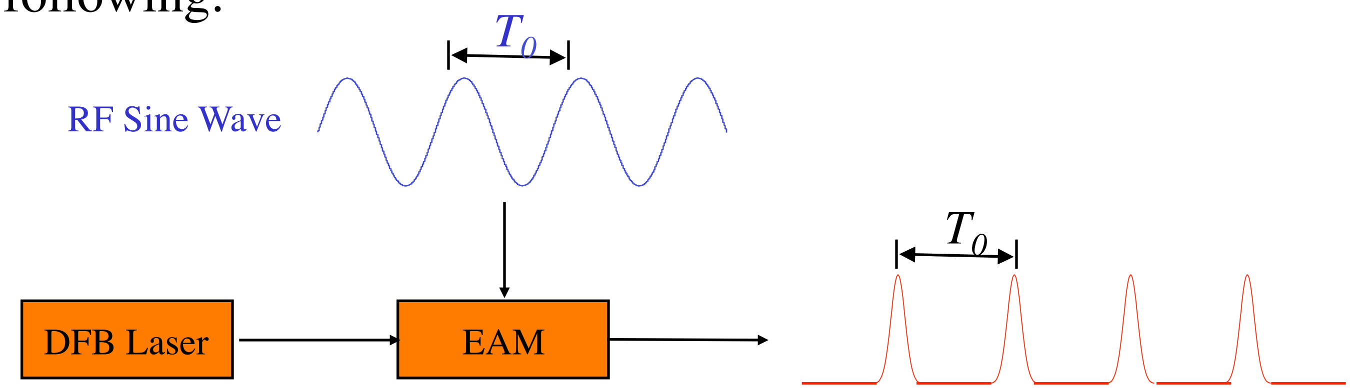
- Several advanced transmission techniques may requires pulsed lasers (RZ or soliton transmission)
  - Their output power vs. time is a periodic train of sharp peaks



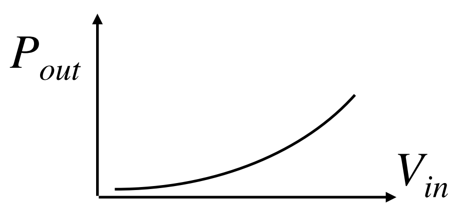
  - The used techniques are:
  - Laser Gain Locking
  - Laser Mode Locking: with this technique, almost perfect, Fourier-limited pulses (small chirp) have been demonstrated

Pulsed Optical Sources

- With the current advance in external modulators, optical pulses are anyway more often obtained using standard external modulation configurations, such as the following:



EAM: Electro-absorption Modulator

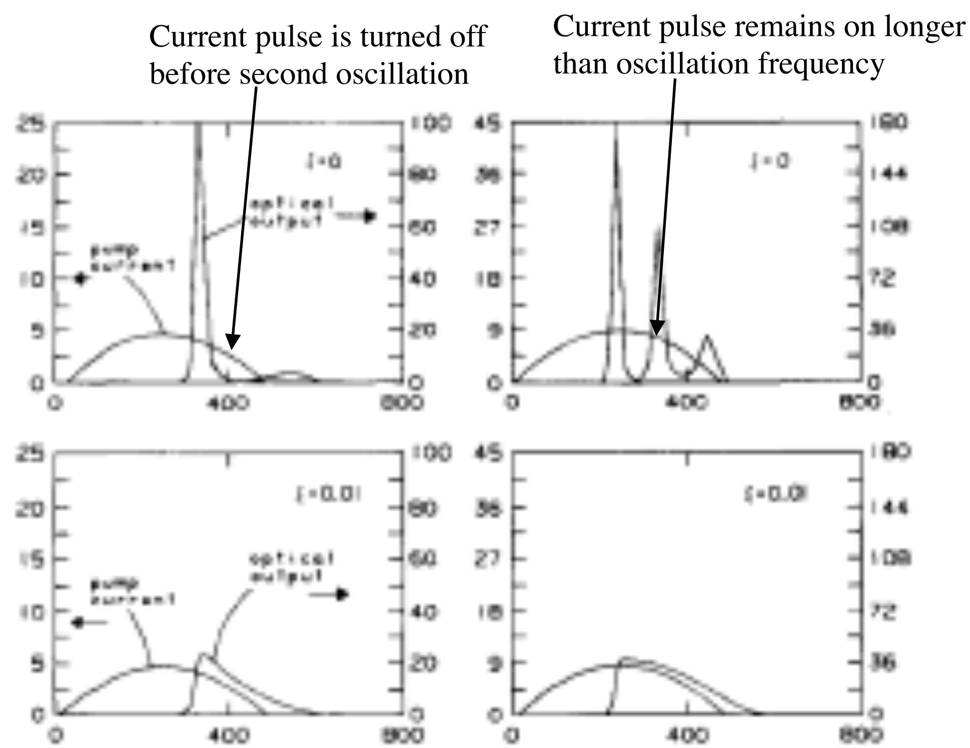


Both EAM or Lithium-Niobate modulators are currently used for RZ generation

Gain Switched Lasers

- Pulses are generated by rapidly modulating the laser gain via the injection current (usually with a sinusoid). The output pulse widths can be shorter than if limited by the carrier lifetime.
- Pulses with nanosecond to picosecond durations can be generated.
- The output pulse repetition rate can be adjusted by changing the frequency and bias of the current drive source.

- The laser is turned on from below threshold, and as we saw before with digital modulation, there will be feedback between the photon and carrier density, causing the laser to oscillate at the relaxation oscillation frequency until it is dampened.
- If the applied current pulse is turned off before the second ringing pulse appears, a very short pulse can be generated.
- In the figures at right, ξ is the gain compression factor which plays the role of dampening

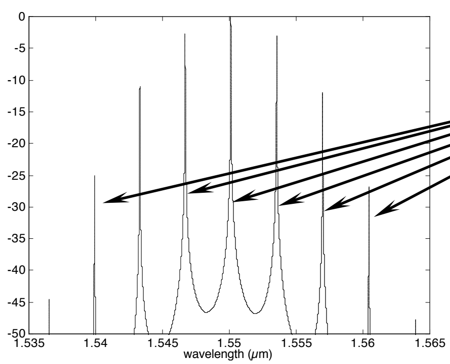


K. Lau, Journal Of Lightwave Technology, Vol. **7.** No. **2.** February **1989**o

Mode-locked Lasers

- Multi-mode lasers emit multiple frequencies that act as independent sources (i.e. the modes are not phase locked with each other). These frequencies are separated (in a FP laser) by the mode spacing Δν = c/2nL. Consider M = 2S+1 modes.
- If we use a means to lock the phase of these modes together, then the laser modes at as a single coherent source and we can apply the Fourier Transform to see that the laser will emit a periodic pulse train

Multi-Mode Laser



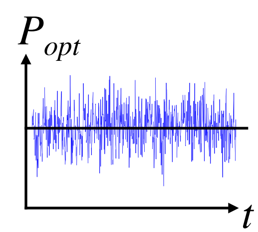
Independent oscillating modes

Mode amplitude

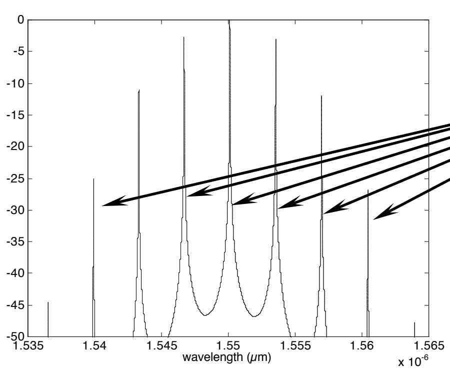
$$E_{out,total} = \sum_{i=-S}^{S} E_i \cos(\omega_i t + \phi_i)$$

Mode frequency

Independent random variable



Mode-Locked Laser



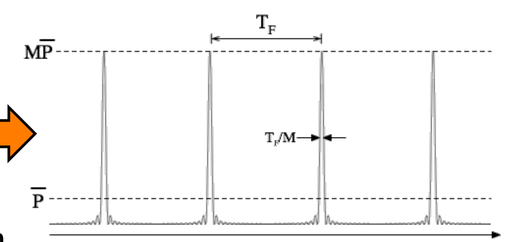
Phase-locked oscillating modes

Mode amplitude

$$E_{out,total} = \sum_{i=-S}^{S} E_i \cos(\omega_i t + \phi)$$

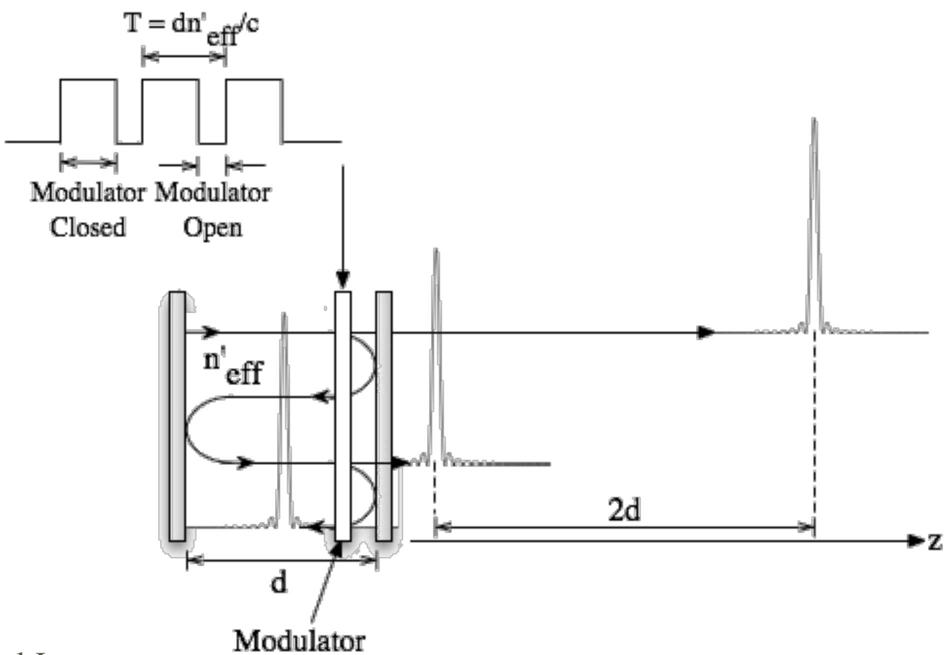
Mode frequency

Fixed phase for each mode



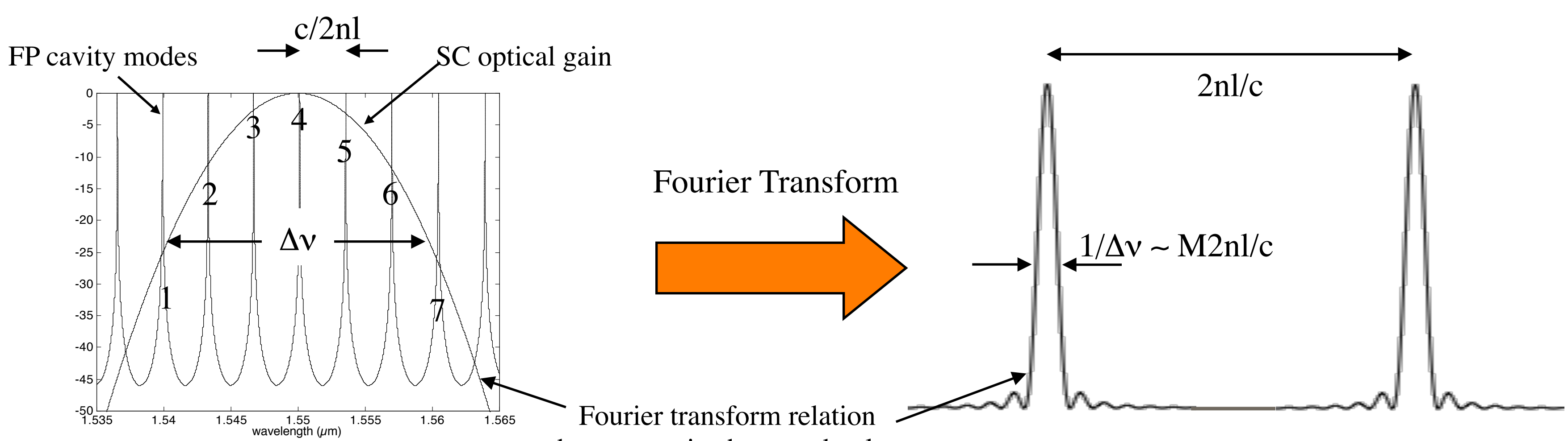
Mode Locked Lasers

- In order to lock the modes together; a loss element that is periodically modulated is placed inside the cavity. The modulater is driven at a frequency that creates a low loss condition only for pulses that match the cavity length.
- The cavity phase relationship will only be reinforced for this set of pulses, and energy that exits the cavity (in the form of these pulses) will be coherent with the cavity round trip time.
- Note that the modulator has to let pulses pass through going both directions in the cavity, hence it runs at twice the rate as the pulses exiting the cavity.



Mode Locked Lasers

- Consider a laser that in steady state (non-modulated) contains M modes. Recall that the spacing between the modes is determined by the resonator (s) and the overall mode shape is determined by the material gain bandwidth as shown below. These can be treated as independent oscillators (incoherent w.r.t. each other).
- Once the modulator is turned on (at a rate equal to the cavity transit time), pulses are emitted from the cavity. The shape of these pulses is determined by the coherent superposition of phase locking the original modes together. Fourier Transform theory tell us the relationship between the frequency and time domain.



Laser modes in steady state operation

FT of laser modes during mode-locking

Transmitters

- Ethernet
  - GigE
  - 10GigE
  - 100GigE
- Fiber Channel
- SONET: Synchronous Optical Network
  - OC-3 (155 Mbit/s)
  - OC-12 (600 Mbit/s)
  - OC48 (2.5 Gbit/s)
  - OC 192 (10 Gbit/s)
  - OC 768 (40 Gbit/s)

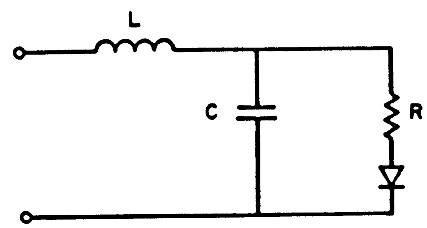
- Transmitter contains laser diode, possibly a modulator, bias circuits, amplifiers, framing chips, optical isolator, etc.

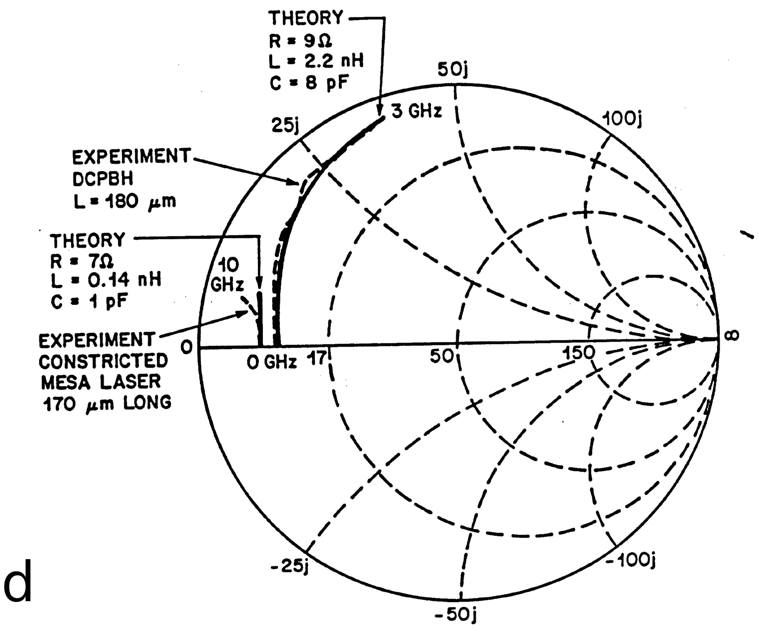
Laser Impedance

Model for laser impedance, consisting of bond-wire inductance, parasitic capacitance and series resistance.

Measurements show microwave characteristics of two mounted laser structures:

- a constricted mesa laser
- a high power dual-channel planar buried heterostructure laser (DCPBH)





Inductance and resistance are determined
from measurement of forward biased laser
(as shown). Capacitance can be found
from reverse biased measurement