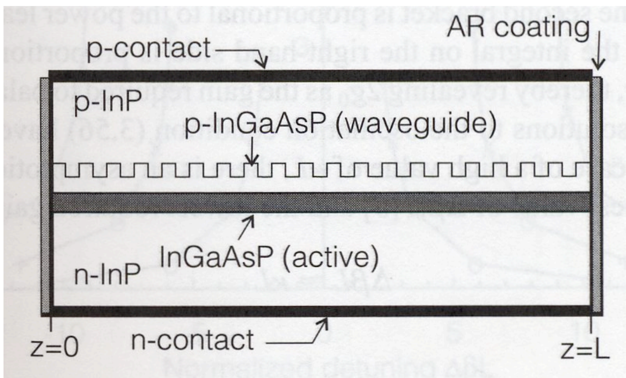
Lecture 6: Single Mode, Tunable Lasers

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



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

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

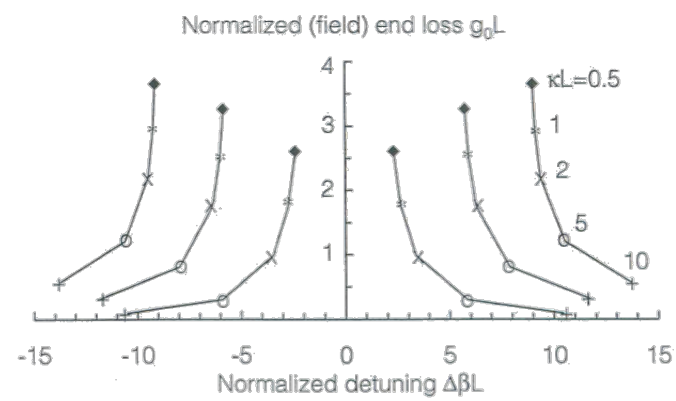
Oscillation Condition: $\gamma L \coth(\gamma L) = -j\left(\Delta\beta L + jg_0 L\right) = 0$

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

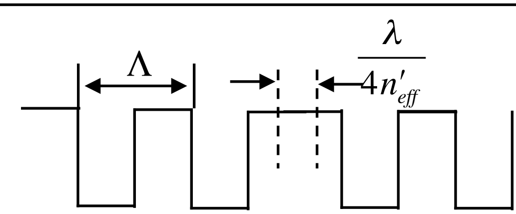
$$\underbrace{\left[\left|R(L)^2\right| - \left|S(L)^2\right|\right]}_{\text{~Power leaving right end of DFB}} + \underbrace{\left[\left|S(0)^2\right| - \left|R(0)^2\right|\right]}_{\text{~Power leaving left end of DFB}} = \underbrace{2g_0\int_0^L \left[\left|R(z)^2\right| + \left|S(z)^2\right|\right]dz}_{\text{~Energy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

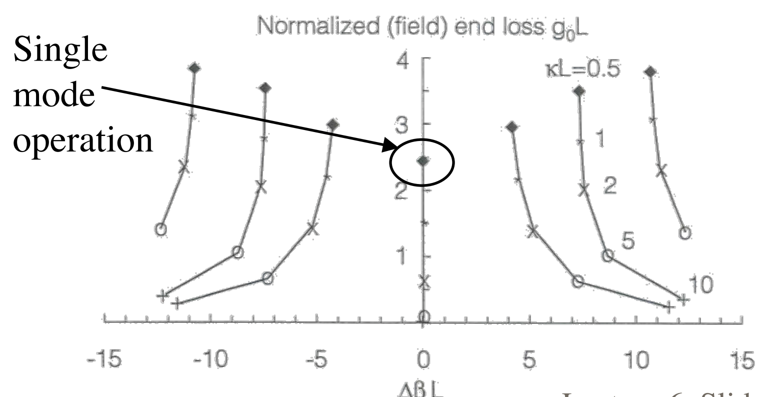
Distributed Feedback (DFB) Lasers

- 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.





Tunable Lasers

Wavelength Tuning Approaches

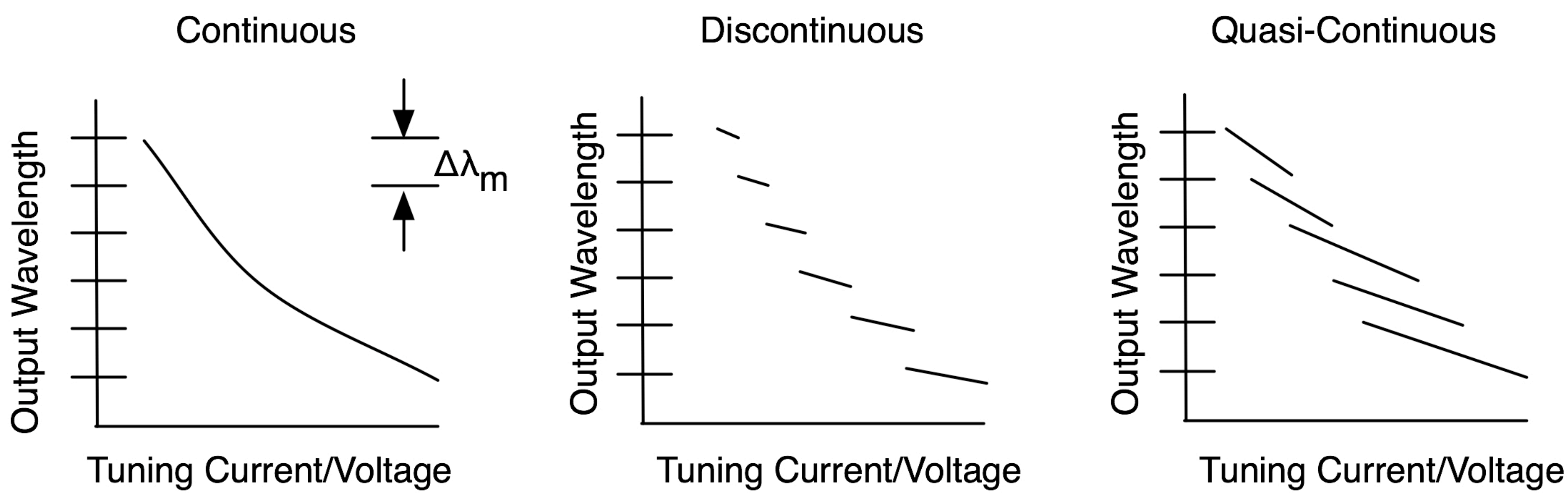
- Mechanical
  - External cavity, MEMs mirror
- Thermal
  - Change affects mirror reflectivity as a function of wavelength
  - Change affects phase or gain of semiconductor laser medium
- Current/Voltage
  - Cavity phase adjustment
  - Cavity mirror vs. wavelength adjustment
  - Cavity filter wavelength adjustment

Wavelength Tuning Metrics

Tuning Parameter	Description
Tuning Range	Output wavelength range (that may need to meet a set of specifications)
Tuning Speed	Time it takes to tune between two output wavelengths (stable)
Tuning Latency	Time it takes for laser (and control electronics) to fully tune after change is requested.
Tuning Continuity	Degree to which all wavelengths are available continuously or discontinuously as a function of changing a control parameter (e.g. current)
Tuning Uniformity	Change in optical characteristics as laser is tuned (and not controlled with feedback circuit). Example includes output power.
Tuning Stability	Short and long term variations (drift) between control (e.g. current) and desired wavelength.
Tuning Accuracy/ Resolution	Error/Precision of achieving a desired wavelength
Optical Characteristics	These include optical power, SMSR, linewidth, bit-rate, chirp and extinction ratio if direct modulated.

Tuning Continuity

- **Continuous:** Laser wavelength is tuned smoothly with change in current/voltage, down to resolution of linewidth. Ideally this approach yields simple control with wide range and complete wavelength coverage.
- **Discontinuous:** Typically involves tuning the gain over many cavity modes. This leads to a discontinuous behavior. This approach can reach a large tuning range but cannot access all of the wavelengths.
- **Quasi-Continuous:** This regime is achieved by tuning cavity modes over small overlapping regions of continuous tuning operation. Both large range and complete wavelength coverage are possible with a tradeoff in control complexity.



Cavity Gain (Loss) Tuning

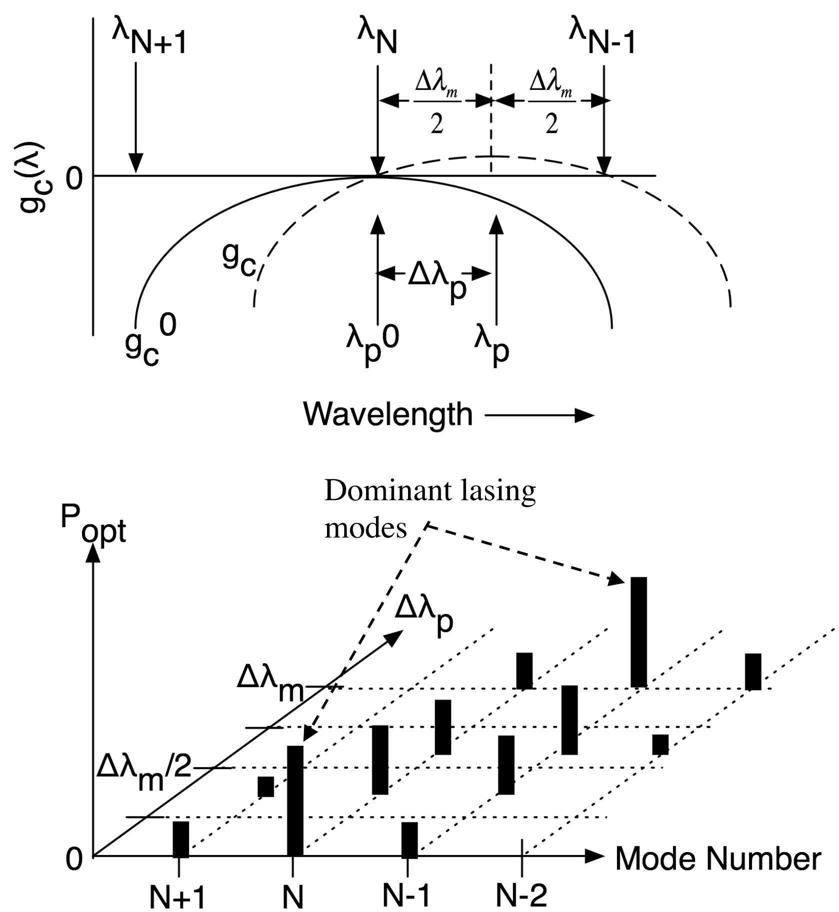
- Tuning $g_c(\lambda) = \Gamma g_a(\lambda) - \alpha_i - \alpha_m(\lambda)$ can be achieved by shifting either
  - Material gain $g_a(\lambda)$ or
  - Mirror loss $\alpha_m(\lambda)$
- As the gain (loss) is tuned, the laser clamps $g_c(\lambda) \approx 0$ at a wavelength that is not the gain peak.
- As the gain (loss) is tuned such that

$$\Delta\lambda_p \le \frac{\Delta\lambda_m}{2}$$

  - The laser will laser in the nearest (lowest loss) mode, which in this example is λ_N
- As the gain (loss) is tuned such that

$$\Delta\lambda_p \ge \frac{\Delta\lambda_m}{2}$$

  - The lasing mode λ_N will cease to lase and λ_{N-1} will start lasing, etc.
- Only discontinuous, discrete modes spaced by $\Delta\lambda_m$ are available using this technique
- Note the SMSR only peaks every $\Delta\lambda_m$ and otherwise is poor

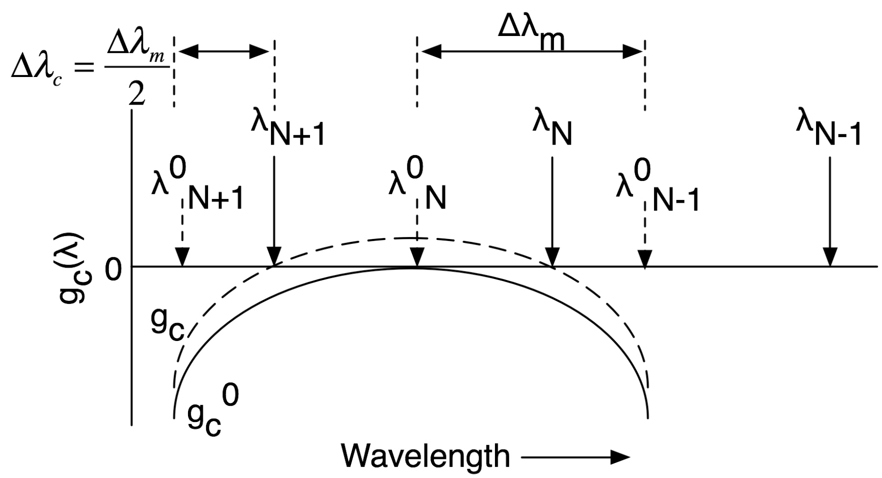


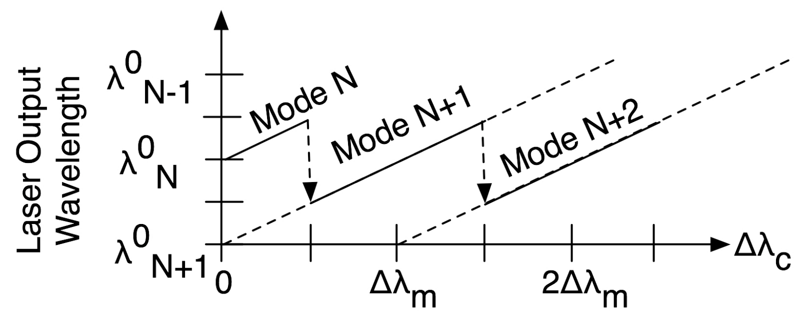
Comb-Mode Spectrum Tuning

- Keeping λ_p fixed and instead tuning the complete mode spectrum (λ_i) such that †

$$\lambda_i = \lambda_i^0 + \Delta\lambda_i$$

- The mode spacing can be adjusted by
  - Varying the physical length of the laser cavity, as is done with an external cavity laser OR
  - Varying the index of refraction of the cavity medium through current or voltage control
- The gain peak stays fixed, however the gain curve moved up and down as the dominant lasing mode is clamped.
- Laser will linearly tune until the cavity has been changed by $\Delta\lambda_c = \Delta\lambda_m$, or one free spectral range, then the output will reset back to original wavelength.
- So the tuning range using comb tuning only is $\Delta\lambda_m$

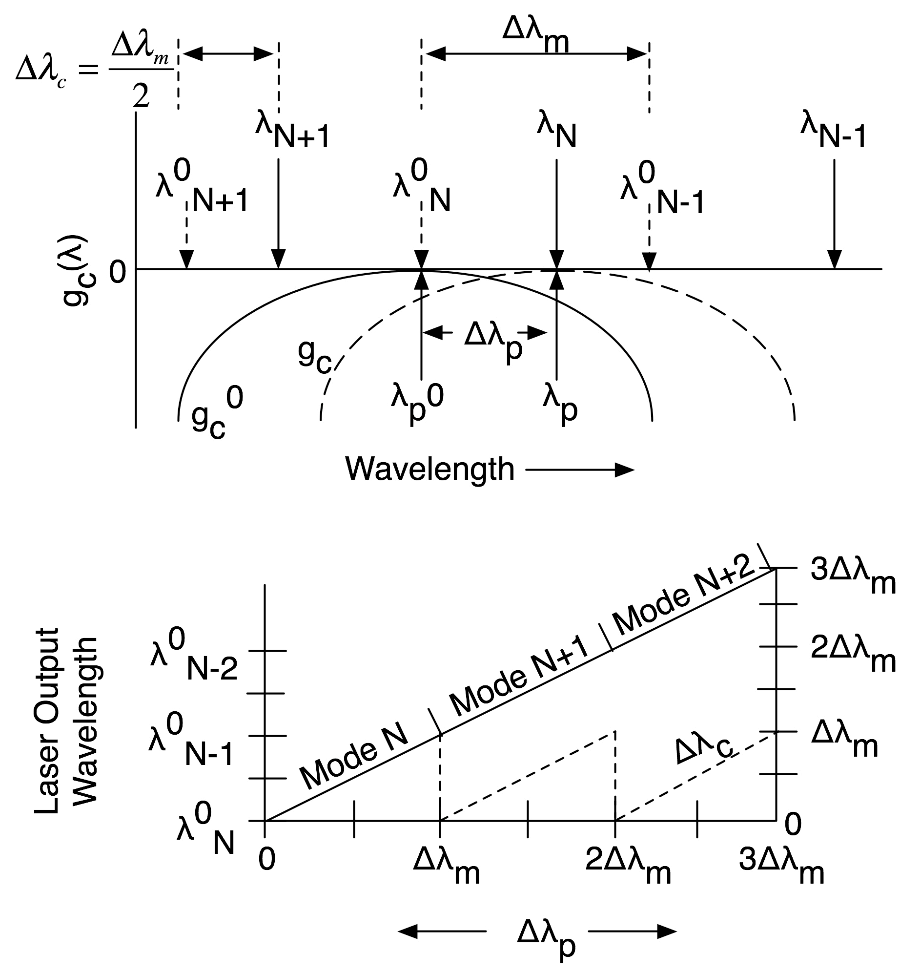




† Note that cavity length changes in spectrum are uniform in frequency but not in wavelength, so this is a good approximation over some limited (but relevant here) optical bandwidth.

Simultaneous Gain and Comb Tuning

- By tuning both $\Delta\lambda_p$ and $\Delta\lambda_c$ at the same time, quasi-continuous tuning can be achieved
- A good example is to track the comb peak with the gain peak such that $\Delta\lambda_p = \Delta\lambda_c = \Delta\lambda$
- Continuous range tuning is limited by the smaller of $\Delta\lambda_{tune,p}$ or $\Delta\lambda_{tune,c}$ which are the limits of gain peak wavelength tuning and comb spectrum tuning respectively
- Quasi-Continuous Tuning Condition:
  - For of $\Delta\lambda_{tune,p} \geq \Delta\lambda_{tune,c}$ and $\Delta\lambda_{tune,c} \geq \Delta\lambda_m$,



Free-Carrier Plasma Effect

- Most frequently used tuning mechanism today and results in the largest tuning ranges reported to date
- For waveguides with bandgap energy much larger than the photon energy of interest, the dominant effect is carrier polarization induced changes in Δn due to current injected electron-hole plasma
- A second effect of equal magnitude is change in index due to change in band-to-band absorption shape due to current injected electron-hole plasma
- The index change, resulting loss change (via Kramers-Kronig) and equivalent linewidth enhancement factor due to carrier injection N=P in an un-doped semiconductor is given by

$$\Delta n' = -\frac{q^2\lambda^2}{8\pi^2 c^2 n\varepsilon_0}\left(\frac{1}{m_e}+\frac{1}{m_h}\right)N = \beta_{pl}N$$

$$\alpha_{pl} = -2k_0\Delta n'' = \frac{q^3\lambda^2}{4\pi^2 c^3 n\varepsilon_0}\left(\frac{1}{m_e^2\mu_e}+\frac{1}{m_h^2\mu_h}\right)N = k_{pl}N$$

$$\alpha_{H,pl} = -\frac{\Delta n'}{\Delta n''} = 2k_0\frac{\Delta n'}{\alpha_{pl}}$$

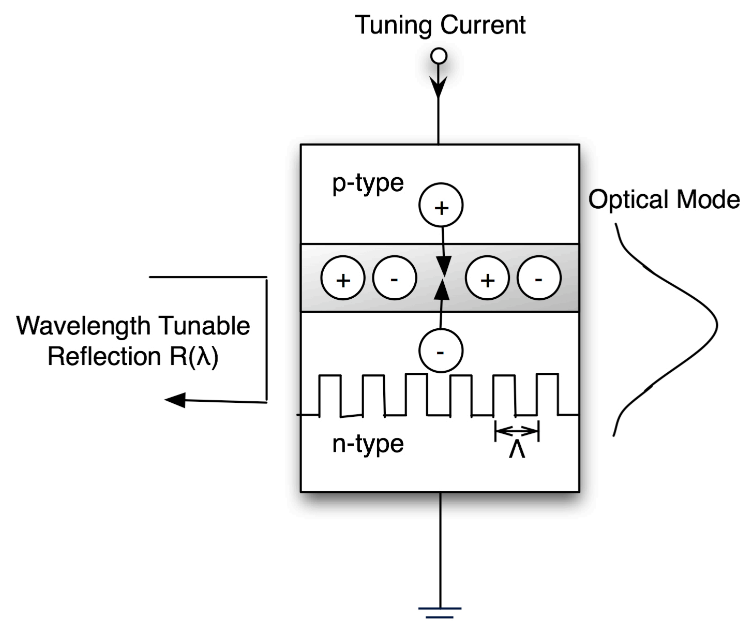
Free-Carrier Plasma Effect

- ⇨Examples:
  - ⇨Phase Tuning: Current injection is used to tune the bandgap (refractive index) of a passive waveguide
  - ⇨Mirror tuning: Current injection is used to tune the effect Bragg wavelength of a periodic waveguide mirror.
- ⇨ Bragg Mirror Tuning:
  - ⇨The change in effective index of refraction for the Bragg material due to injected carriers is

$$\Delta n_{eff} = \Gamma_t \Delta n_t$$

  - ⇨The resulting change in the Bragg wavelength due to the injected current density is

$$\Delta\lambda = \frac{\beta_{pl}\Gamma_t\lambda_B}{n_{g,eff}} N$$

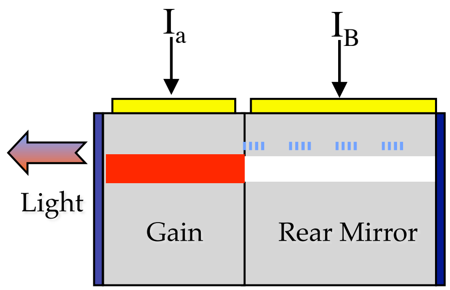


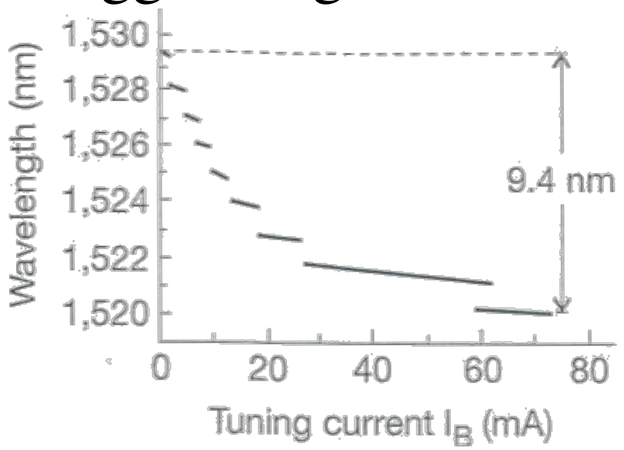
Thermal Tuning of DFB Lasing Wavelength

- The gain peak (g_p) of semiconductor gain is dependent on temperature and can be thermally shifted. This is due to temperature dependence of the bandgap energy
  - Typical gain peak shift is 0.5nm/$°K$
- A change in temperature also changes the index of refraction. For the DFB this shifts the Bragg wavelength
  - Typical resonator frequency shift is 0.5nm/ $°K$
- Note that for the DFB, the lasing wavelength is determined by the Bragg wavelength (not the gain peak). However the shift in gain peak will determine the laser output power.

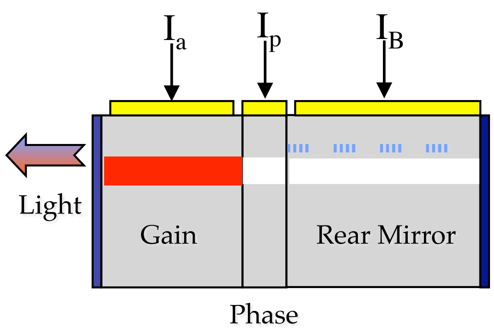
Longitudinally Integrated Tunable Structures

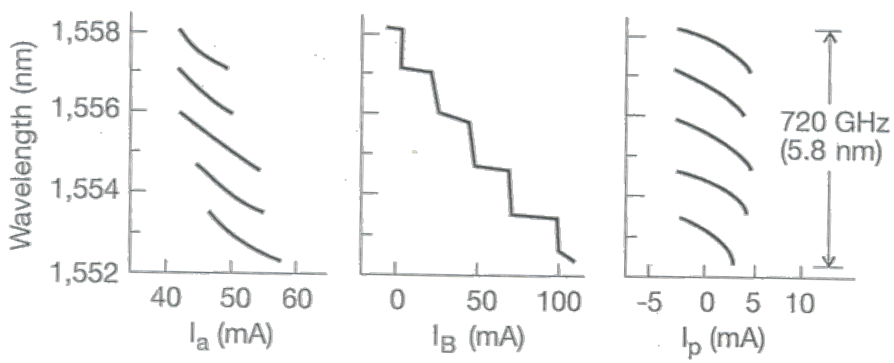
⇨ 2-Section DBR with passive Bragg tuning section





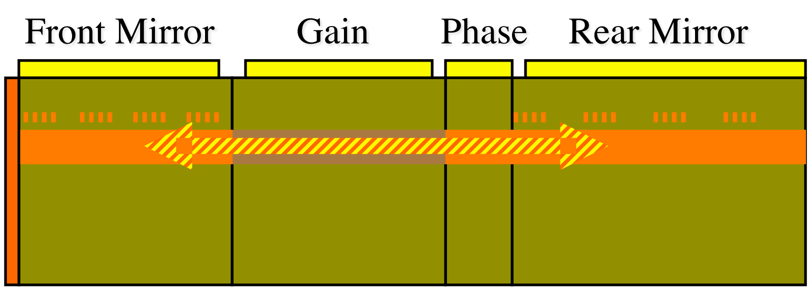
⇨ 3-Section DBR with passive Bragg tuning section

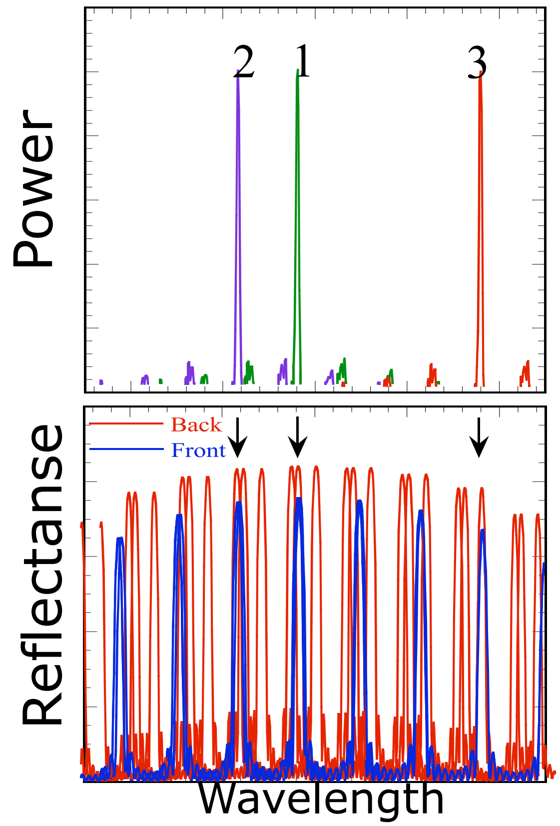




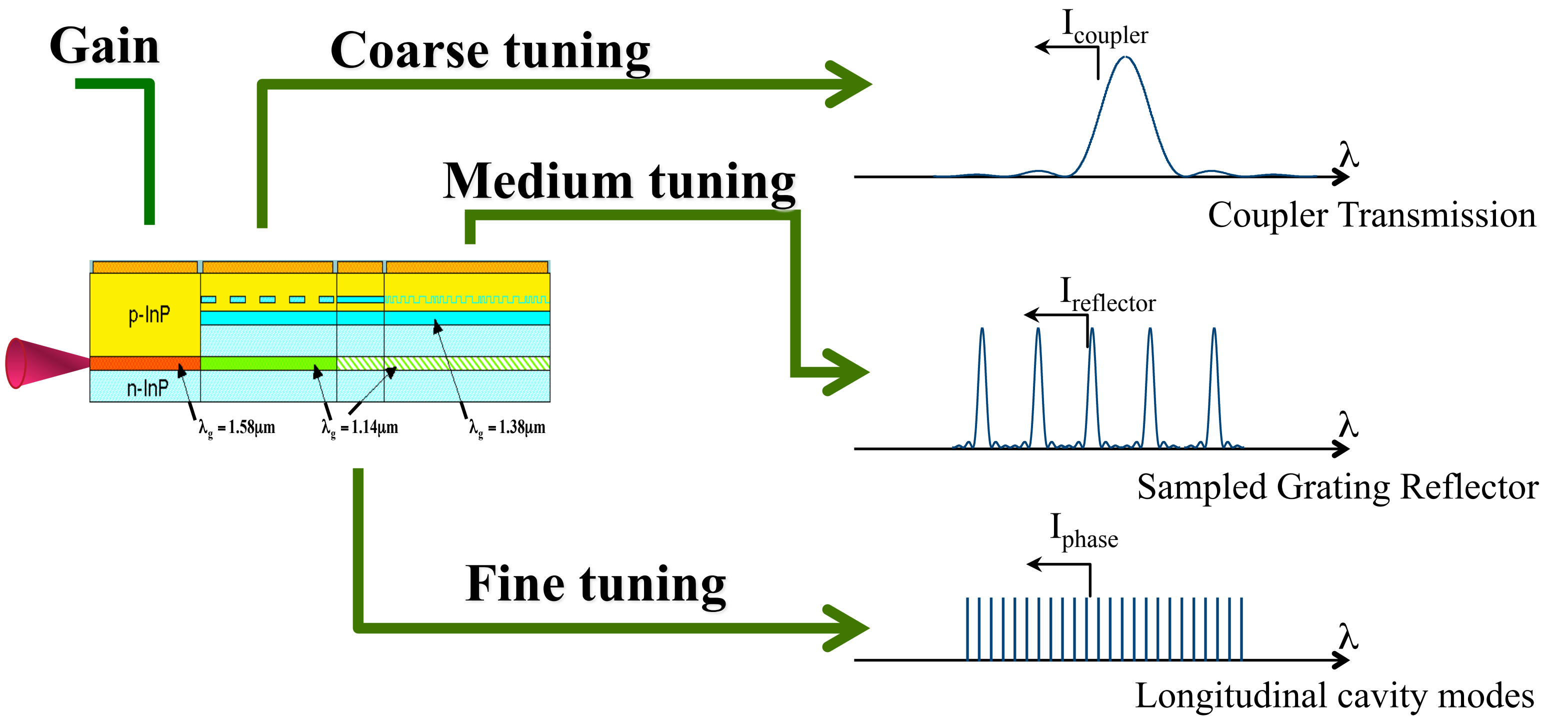
Widely Tunable Integrated Structures

- Sampled Grating DBR Lasers





GCSR: Grating Coupled Sampled Reflector



Phase

GCSR Tuning Curves