Semiconductor Lasers :
Output Characteristics & SM Lasers

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OUTLINES

I. Output Characteristics of Laser

a. Threshold Current
b. Confinement Factor
c. Spatial Profile
d. Longitudinal modes

II. Single Mode lasers

a. ECL
b. DFB & DBR lasers
c. VCSELs
d. Quantum Lasers

Basic Laser Theory

Oscillator = Gain Medium + Feedback (Resonator)

Peak Gain coefficient: $$\boldsymbol{\gamma_p = \alpha_a\left(\frac{\Delta n}{\Delta n_T} - 1\right)}$$

For steady state oscillation : Gain = Resonator loss

threshold peak Gain coefficient: $$\boldsymbol{\gamma_{pt} = \alpha_r = \alpha_s + \frac{1}{2l}\ln\left(\frac{1}{R_1R_2}\right)}$$

Typical Values:-

$\alpha_s \approx 22cm^{-1}$ $\quad$ $l = 300\mu m$

$\alpha_a \approx 600cm^{-1}$ $\quad$ $R_1 = R_2 = 0.32$

$$\boldsymbol{\gamma_{pt}} = 60cm^{-1}$$

Basic theory

$$\gamma_p = \alpha_a\left(\frac{\Delta n}{\Delta n_T} - 1\right)$$

$$\Rightarrow \left(\frac{\Delta n_t}{\Delta n_T} - 1\right) = \frac{\gamma_p}{\alpha_a} = 0.1; \qquad \frac{\Delta n_t}{\Delta n_T} = \frac{J_t}{J_T} = \frac{i_t}{i_T} = 1.1$$

$$i.e. \quad i_t = 1.1 i_T$$

Temperature dependent of threshold current:-

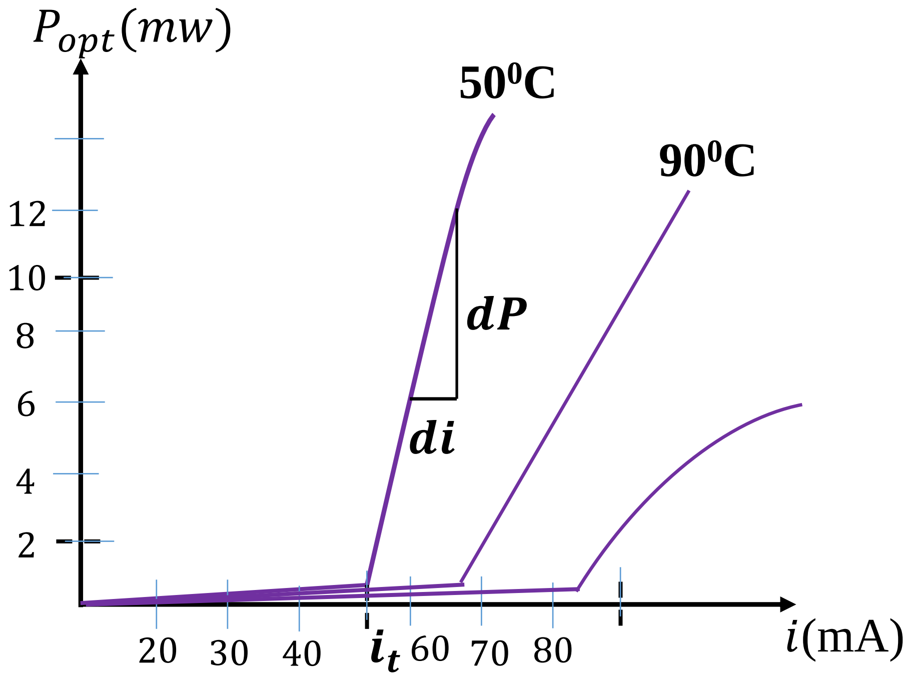
$$i_t(T) = i_0 e^{-T/T_0}$$ **(temperature characteristic)**

Above threshold:-

$$P_{opt} \propto (i - i_t)$$

$$P_{opt} = k(i - i_t)$$

$$\frac{dP}{di} = \text{differential Responsivity (W/A)}$$



Assignment # 2

Why the threshold current increase with increase in the temperature?

Output Characteristics: Threshold current

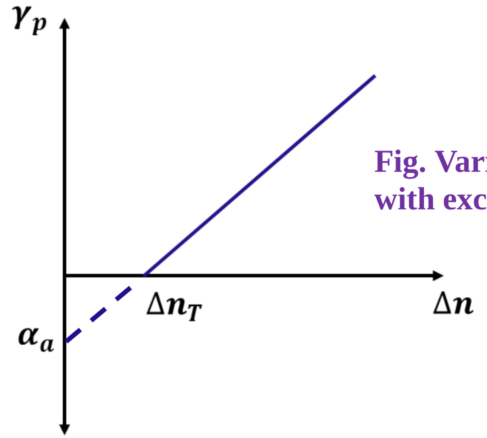


Fig. Variation of Peak Gain coefficient with excess carrier concentration

$$\gamma_p = \alpha_a\left(\frac{\Delta n}{\Delta n_T} - 1\right)$$

$$\Delta n = \alpha_a\left(\frac{(i/e)\tau}{l \times w \times d}\right) = \frac{J\tau}{ed}$$

$$\therefore J_T = \frac{\Delta ned}{\tau} \quad \rightarrow J_T \propto d$$

Laser Condition: Gain = Loss

$$\gamma_{pt} = \alpha_r$$

$$\alpha_a\left(\frac{\Delta n_t}{\Delta n_T} - 1\right) = \alpha_r$$

$$\alpha_r = \alpha_a\left(\frac{J_t}{J_T} - 1\right)$$

$$\therefore J_t = J_T\left(1 + \frac{\alpha_r}{\alpha_a}\right)$$

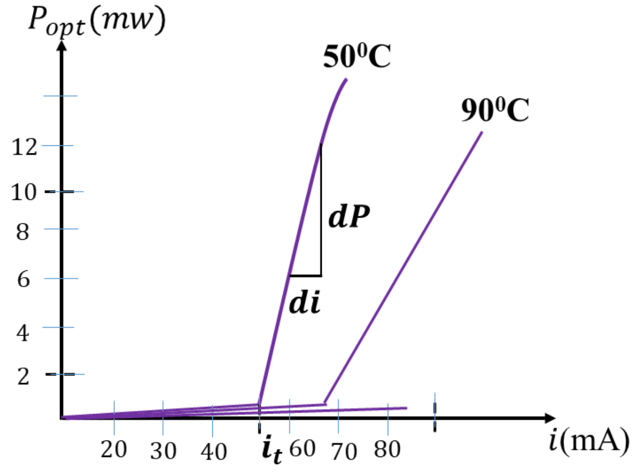
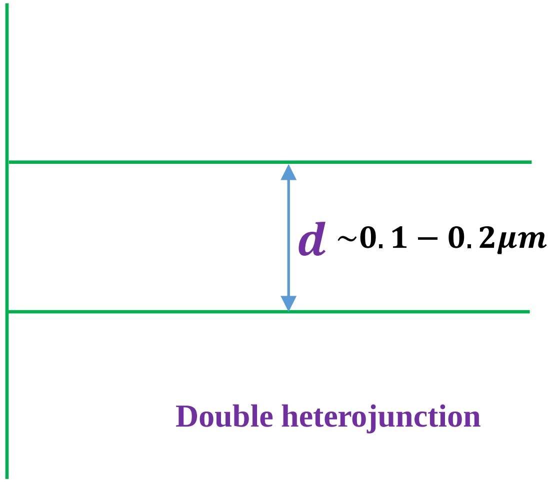
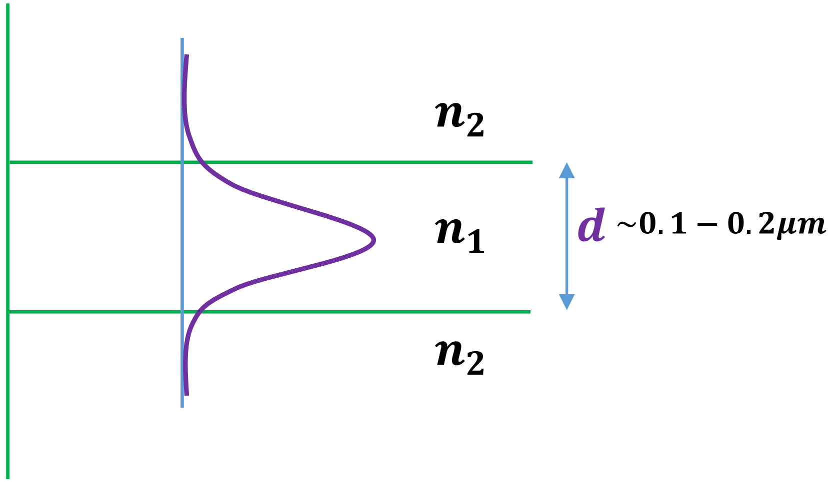


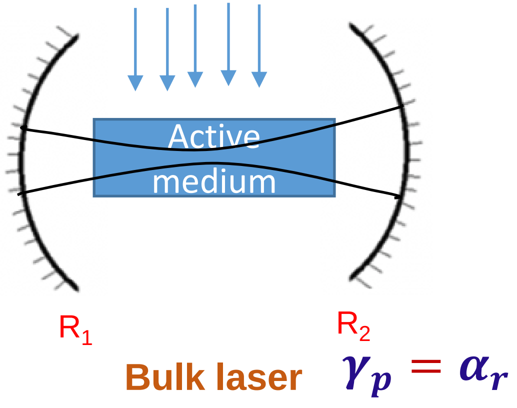
Fig. Threshold current variation with temperature

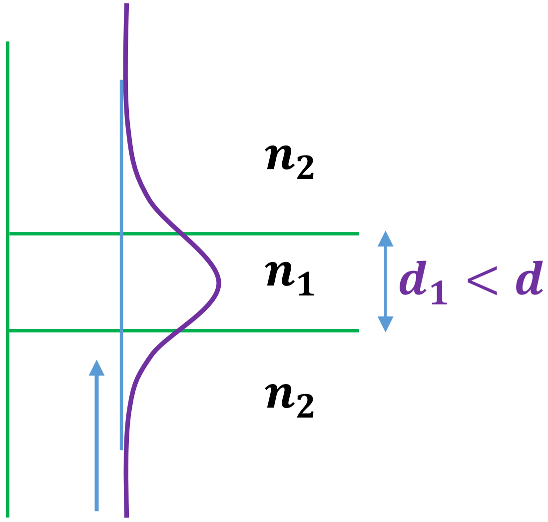


Double heterojunction

Output Characteristics: Confinement Factor, Γ







$\boldsymbol{Confinement\ factor, \Gamma}$ → fractional energy in the active region

$$0 < \Gamma < 1$$

$$cavity\ gain = \Gamma \gamma_p$$

$$\Gamma \gamma_p = \alpha_r = \Gamma \alpha_a \left(\frac{J_t}{J_T} - 1 \right)$$

$$\therefore J_t = J_T \left(1 + \frac{\alpha_r}{\Gamma \alpha_a} \right)$$

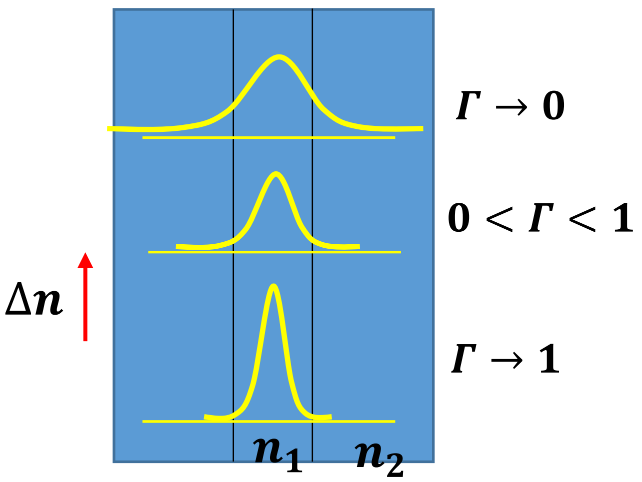
$$penetration\ depth, \frac{1}{\gamma} \rightarrow = 1/\sqrt{\beta^2 - k_0^2 n_2^2}$$

$$V\ number, V = \frac{2\pi}{\lambda} d \sqrt{n_1^2 - n_2^2}$$

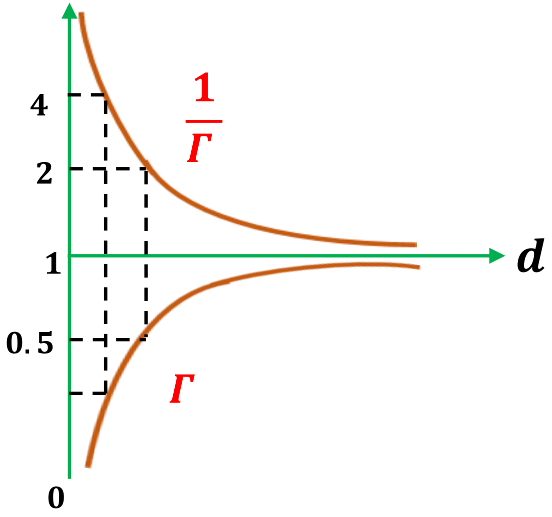
$d \downarrow$ $V \downarrow$ $\beta \uparrow$ $\Gamma \downarrow$

Output Characteristics: Confinement Factor, Γ

$$V\ number, V = \frac{2\pi}{\lambda} d\sqrt{n_1^2 - n_2^2}$$



$\Delta n = (n_1 - n_2)$ ↑ Tightly confined

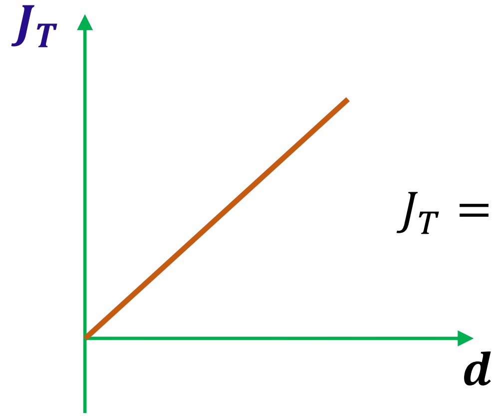


d decreases Γ becomes small ; $\frac{1}{\Gamma}$ becomes large

$$J_t = J_T\left(1 + \frac{\alpha_r}{\Gamma\alpha_a}\right)$$

$$= J_T + \left(\frac{\alpha_r}{\Gamma\alpha_a}\right)J_T$$

most practical value of Γ varies from 0.6 to 0.9



$$J_T = \frac{\Delta n_T e d}{\tau}$$

Fig. transparent current dependence on width of active region

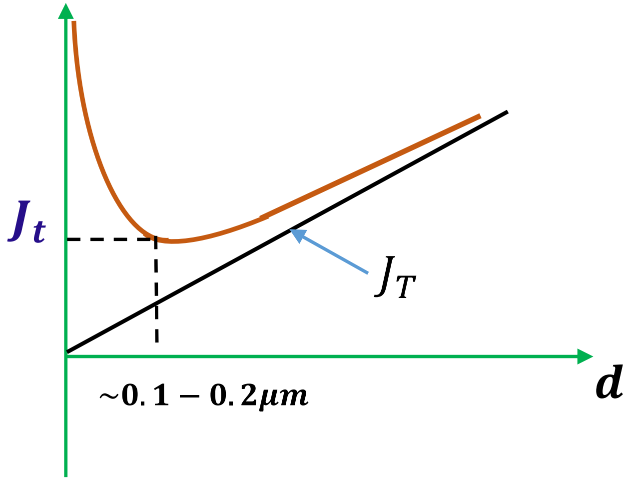
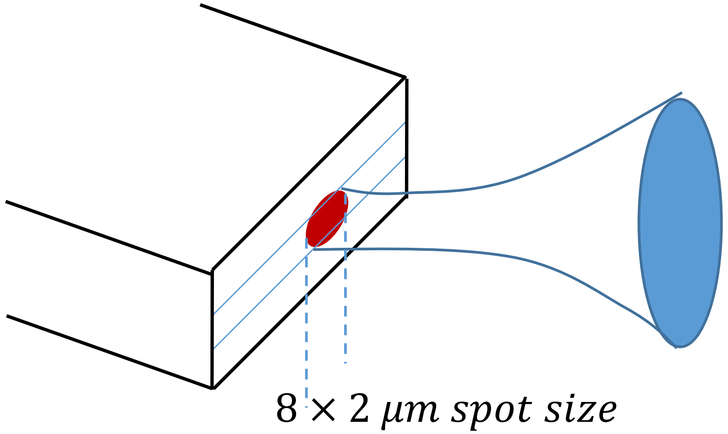
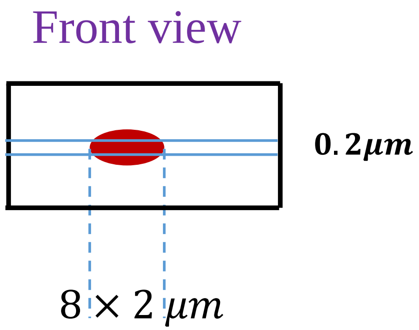


Fig. threshold current w.r.t. width of active region

Output Characteristics: Spatial Profile



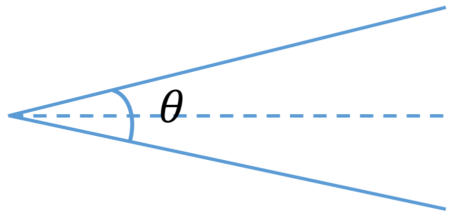


Example:-

$\lambda = 1\ \mu m$

$$\theta_{\perp} \approx \sin^{-1}\left(\frac{\lambda}{d=2}\right) = 30^{\circ}$$

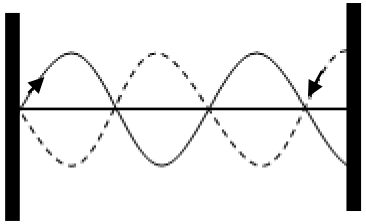
In 2D plane:



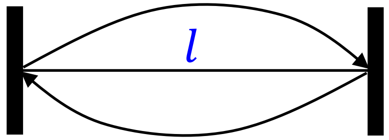
$$\theta_{\parallel} \approx \frac{\lambda}{d} \approx \frac{1}{8}$$

$$\theta_{\parallel} \approx 7^{\circ}$$

Output Characteristics: Longitudinal Modes



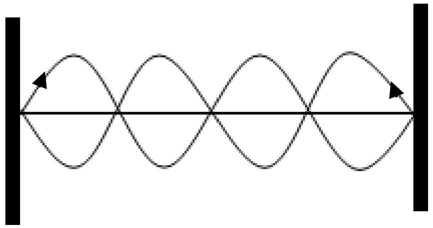
(a) FP resonator with arbitrary wave



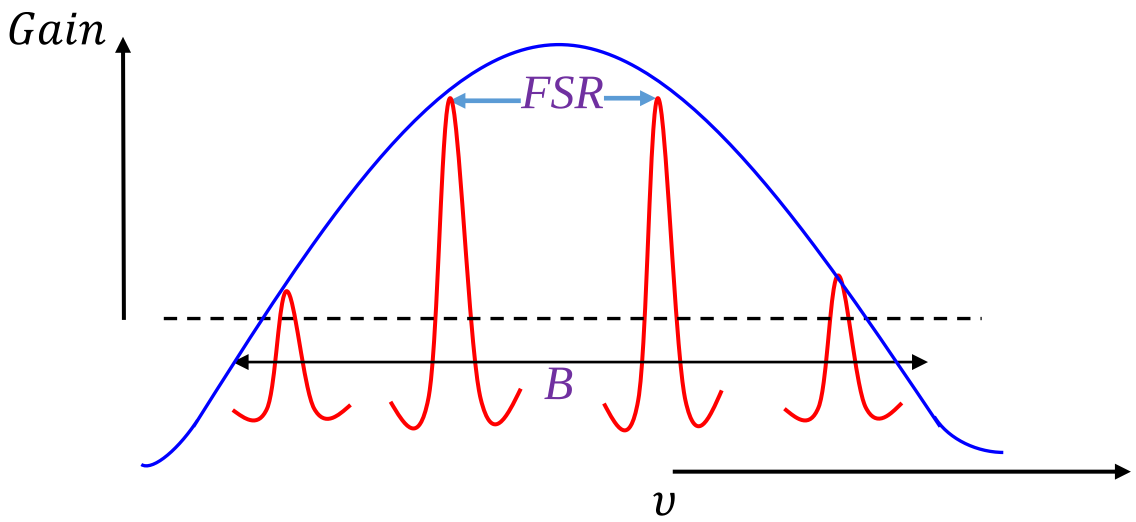
$B \sim 10^{12}\ Hz$

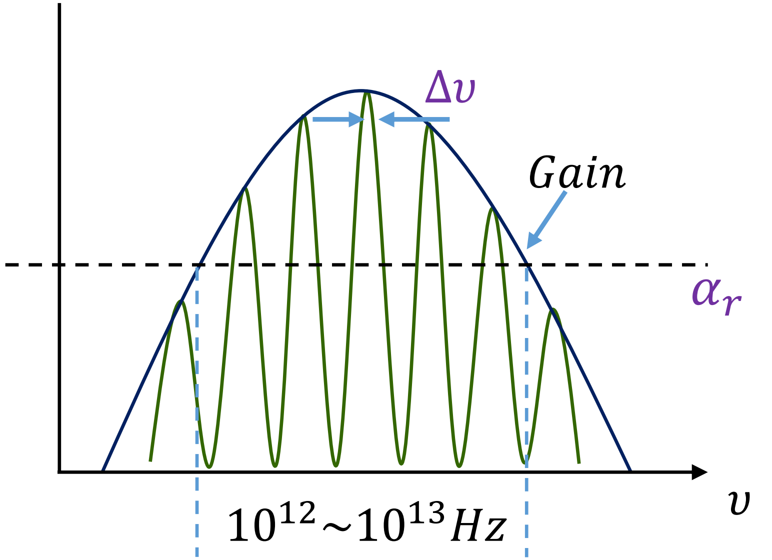
$$\nu_F = \frac{c}{2nl} = \frac{3\times 10^8}{2\times 300\times 10^{-6}\times 3.6} \approx 1.4\times 10^{11} Hz$$

$$\Rightarrow few/several\ longitudinal\ modes = B/\nu_F$$



(b) FP resonator with standing wave





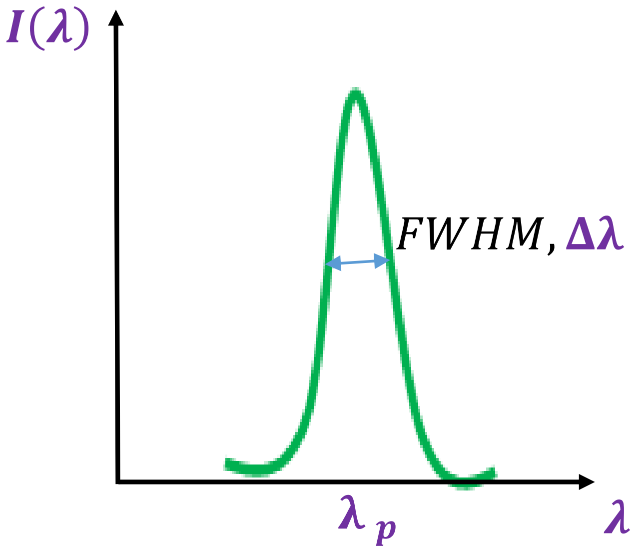
MODE SELECTION: ECL, DFB, DBR LASER

Output Characteristics: Spectral linewidth

$\Delta\lambda \rightarrow linewidth$

Typical:-

$\Delta\lambda \sim 20 - 40$ nm for LED
$\sim 2 - 3$ nm for FP lasers
≤ 0.1 nm for DFB lasers, VCSELS



Equivalence:-

$$\Delta\lambda \leftrightarrow \Delta\nu$$

$$c = \nu\lambda \Longrightarrow \nu = \frac{c}{\lambda}$$

$$\Delta\nu = \frac{c}{\lambda^2}(-\Delta\lambda)$$

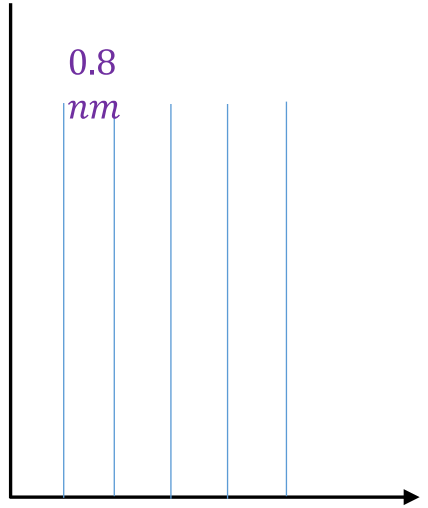
For example:-

$$\lambda = 1.55\ \mu m$$

$$\Delta\lambda = 1\ nm \Longrightarrow \Delta\nu = 125\ GHz$$

$$\Delta\nu = 100\ GHz \Longrightarrow \Delta\lambda = 0.80\ nm$$

$$\Delta\nu = 100\ MHz \Longrightarrow \Delta\lambda = 0.00080\ nm$$



Output Characteristics: Spectral linewidth

Importance of Narrow linewidth

In DWDM

$$\Delta\lambda(source\ linewidth) \ll \delta\lambda(channel\ spacing)$$

For 100 GHz channel spacing: $\delta\lambda = 0.8\ nm$
For 50 GHz channel spacing : $\delta\lambda = 0.4\ nm$

$$\Rightarrow \boldsymbol{\Delta\lambda < 0.1\ nm\ or\ smaller\ for\ no\ channel\ overlap}$$

Dispersion in fiber link

Dispersion parameter: $D = \frac{\Delta\tau}{L\Delta\lambda} ps/km\text{-}nm$ GHz

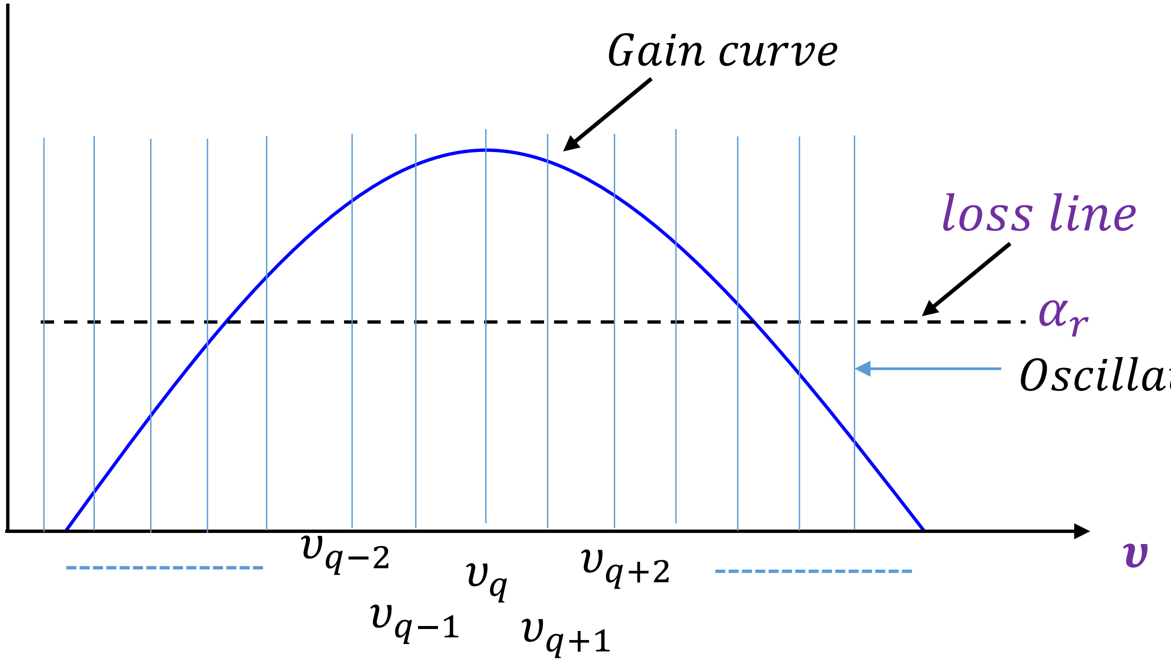
$$\Rightarrow \boldsymbol{\Delta\tau = D \times L \times \Delta\lambda}$$

$\Delta\tau$: *Temperoal spread of a pulse*
L: *length of the link*
$\Delta\lambda$: *Source Linewidth*

$$\Rightarrow \boldsymbol{smaller\ the\ \Delta\lambda, smaller\ is\ the\ spreading\ of\ the\ pulse, \Delta\tau}$$

$$\Rightarrow \boldsymbol{larger\ bit\ rates\ are\ possible\ without\ ISI}$$

Output Characteristics: multi-longitudinal mode oscillation

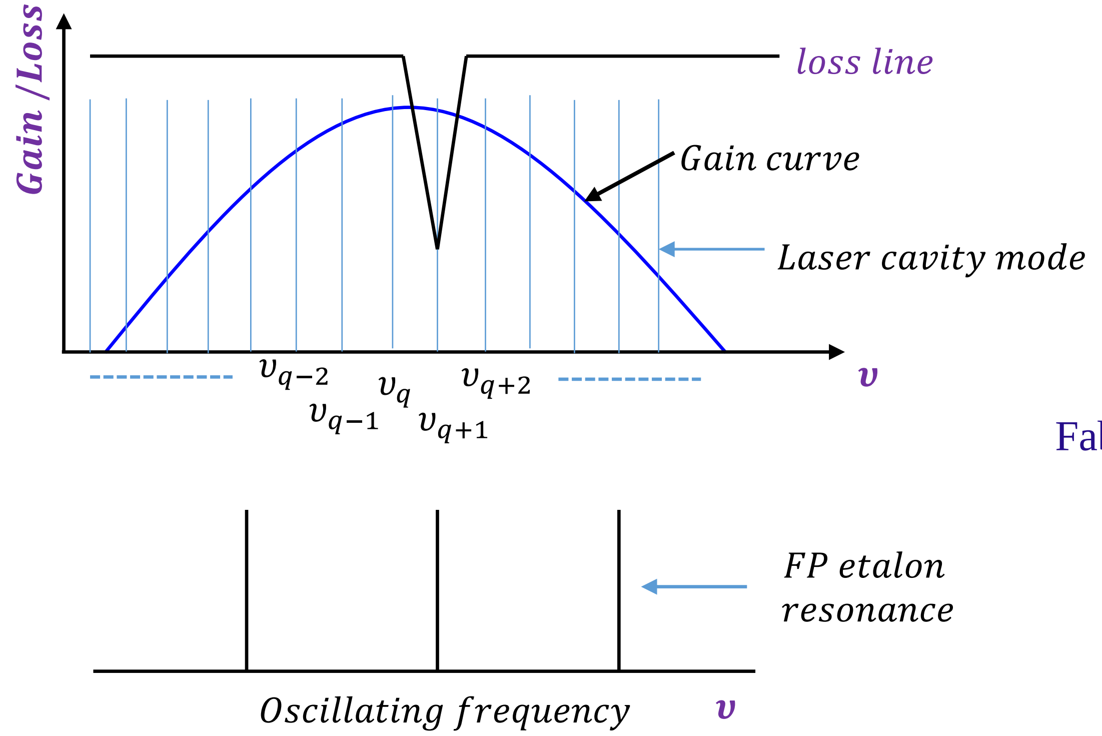


Those modes which have gain more than loss will be able to oscillate leading to multi − frequency oscillation.

In the figure shown above, oscillation will occur at *Eight* frequencies

Output Characteristics: Single Frequency Oscillation

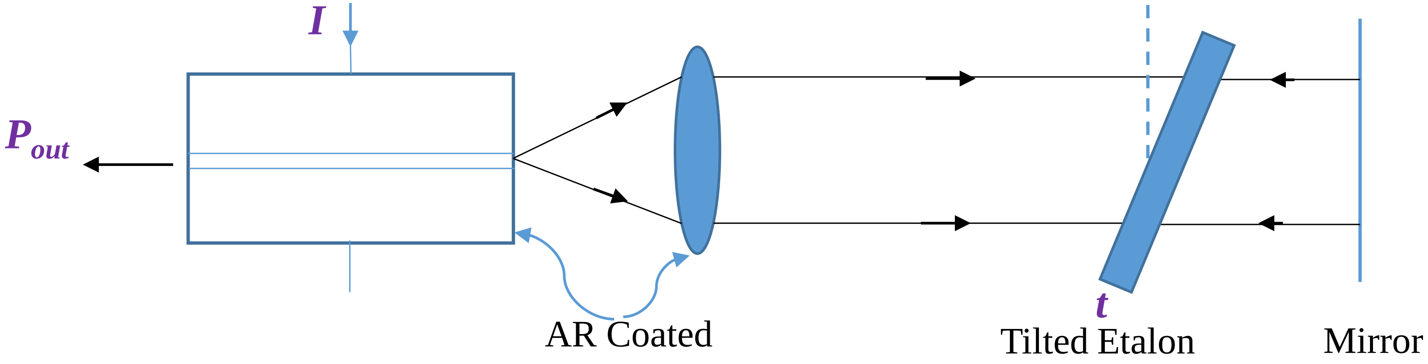
Multi-frequency oscillation leads to large source linewidth

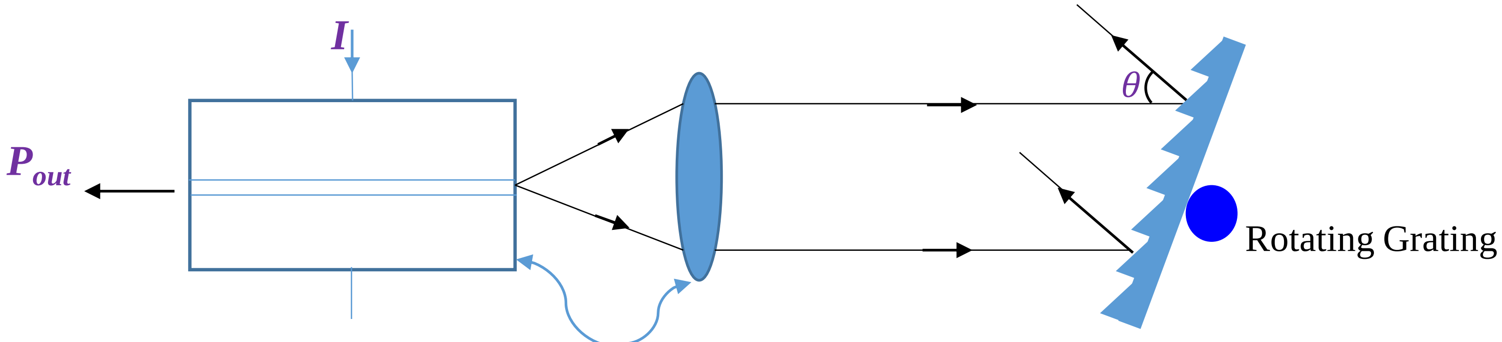


Fabry Perot cavity with a small thickness *t*

Why the etalon of small thickness is used?

Single Frequency Lasers: External cavity

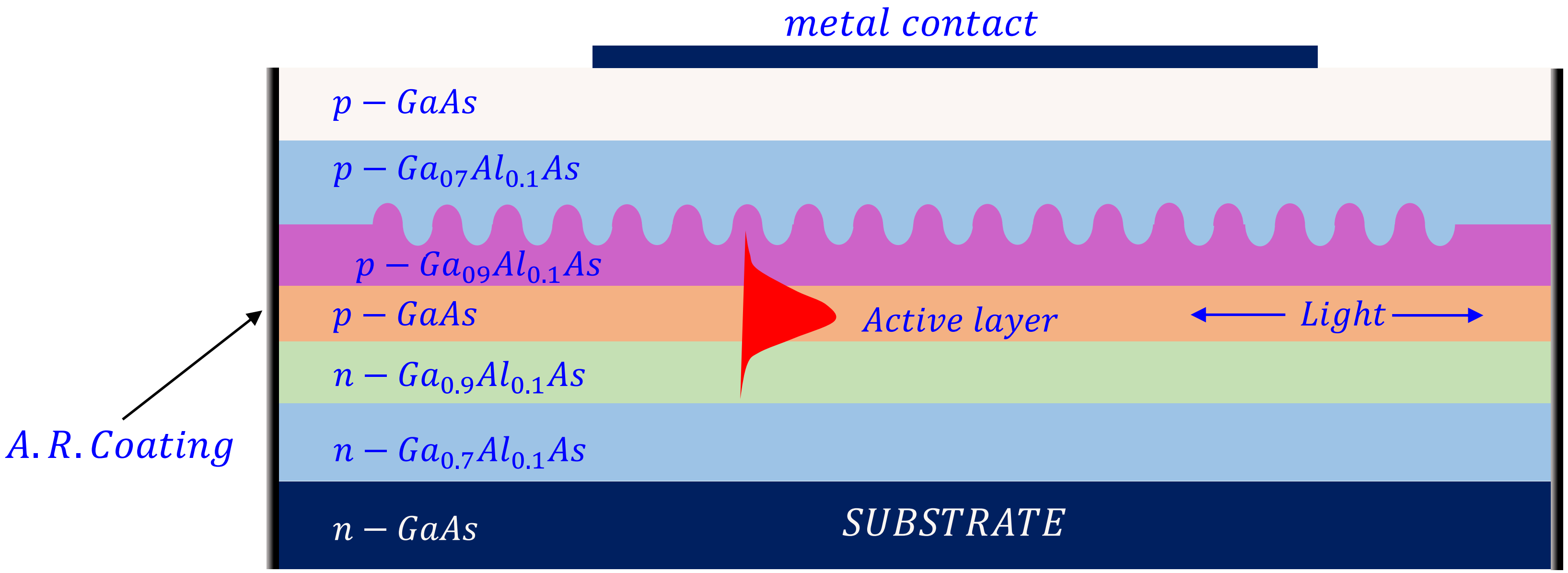




$$\lambda_0 = 2\Lambda \sin\theta$$

At a given angle, the only one frequency will be selected which satisfy the above equation
Lossy cavity for other wavelengths
Maximum tuning up to 50 nm for ECL

Single Frequency Lasers: DFB Laser

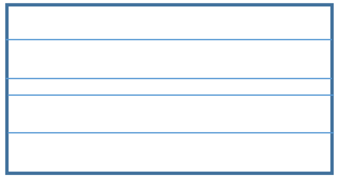


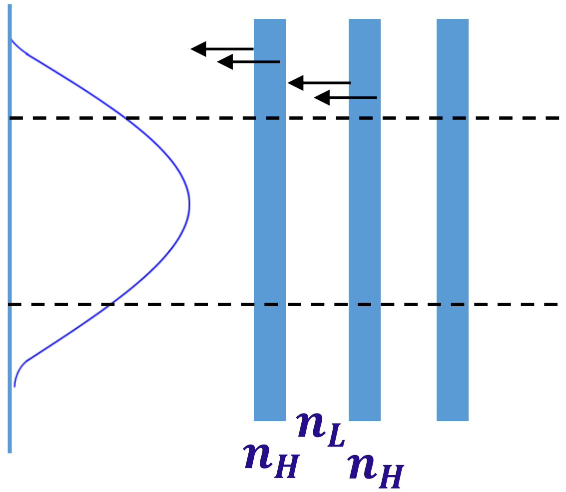
For resonant backward reflection: $\frac{2\pi}{\lambda_0} n_{eff} 2\Lambda = q \times 2\pi \;\; ; q = 1$ *for first order grating*

Required grating period: $\Lambda = \frac{\lambda_0}{n_{eff}}$

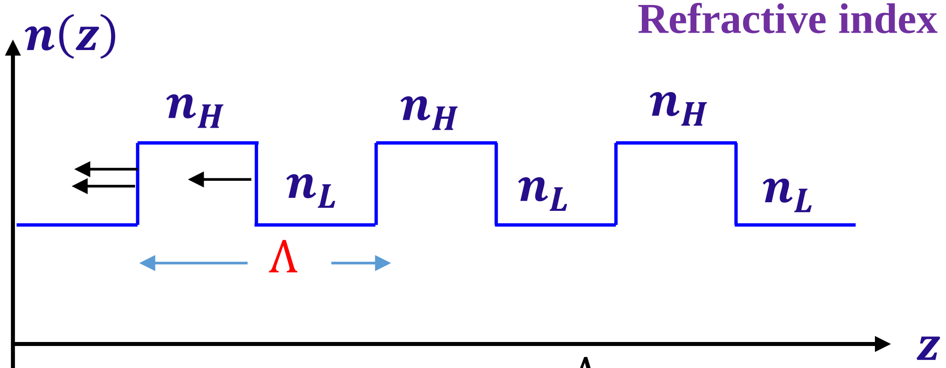
n_{eff}: *effective index of the guided mode* $\approx n_{average}$

Single Frequency Lasers: DFB Laser



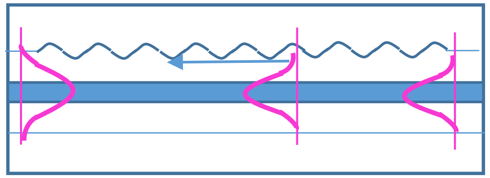


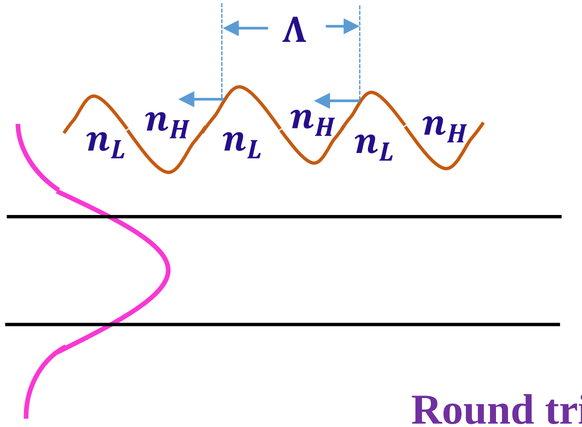
Refractive index variation



$$\Delta\phi = 2k_0 n \frac{\Lambda}{2} = \pi$$

$$\frac{2\pi}{\lambda_B} n\Lambda = \pi$$





$$2k_0 n_{eff}\Lambda = q \times 2\pi$$

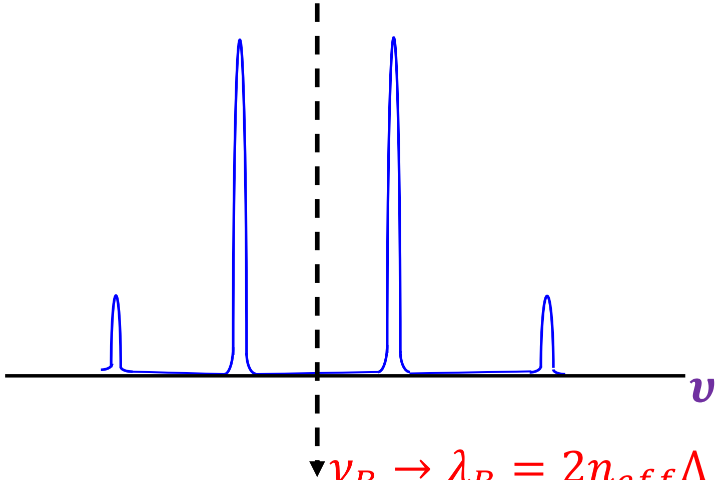
$$\Lambda = \frac{\lambda_0}{2n_{eff}}$$

For $\lambda_B = 1.55\mu m$

$$\Lambda = \frac{1.55}{2 \times 3.5} \approx 0.23\ \mu m$$

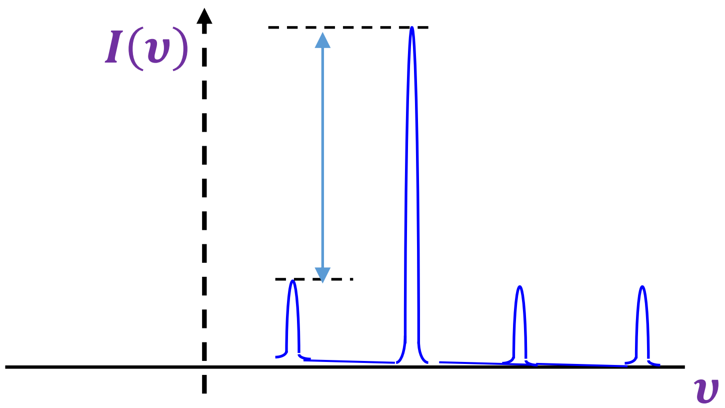
Round trip phase is integral multiple of 2π, feedback is only for λ_0

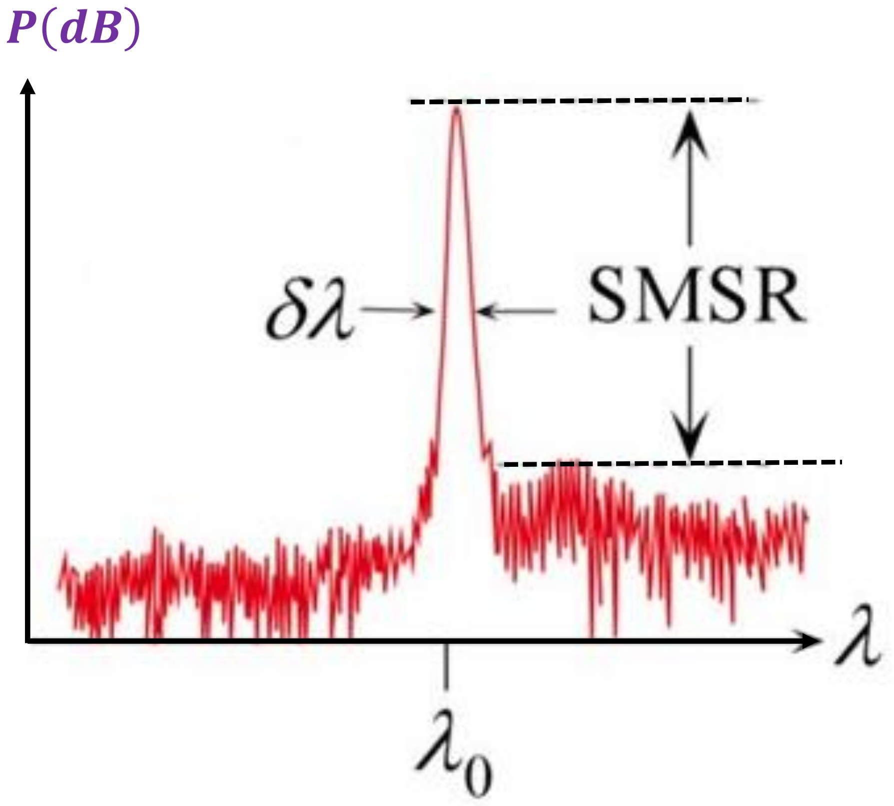
Single Frequency Lasers: DFB Laser



$$\nu_B \to \lambda_B = 2n_{eff}\Lambda$$

$$= \frac{c}{2n_{eff}\Lambda}$$



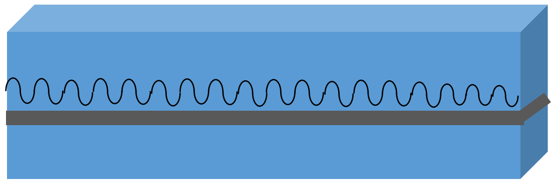


Output spectrum of DFB Laser

<u>But actually the frequency is slightly shift at the laser output</u>

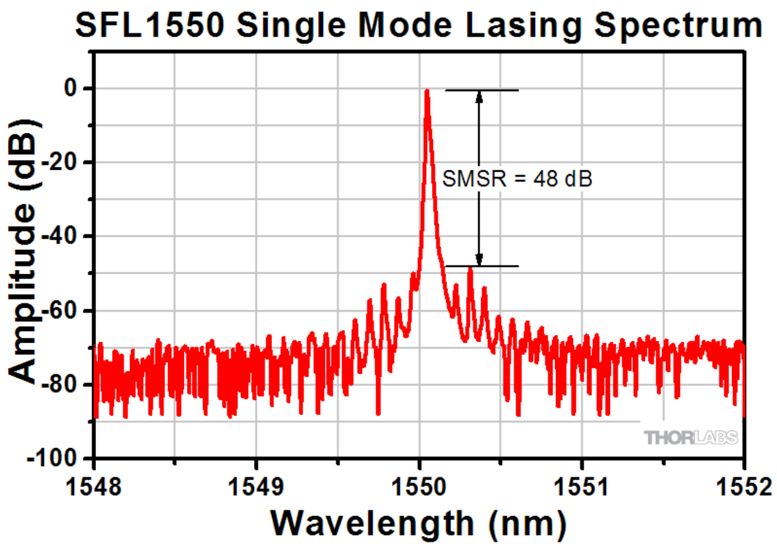
$$\nu_L = \nu_B \pm \left(\frac{c}{2n_{eff}l}\right)\left(q + \frac{1}{2}\right)$$

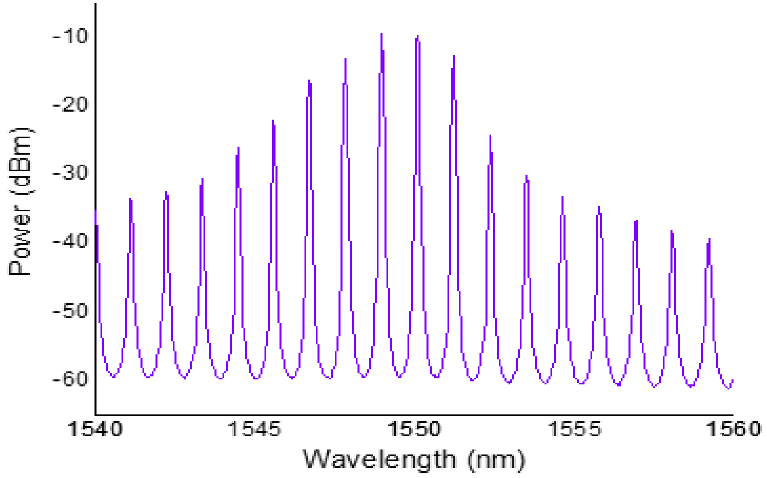
Single Frequency Lasers: Output Spectrum



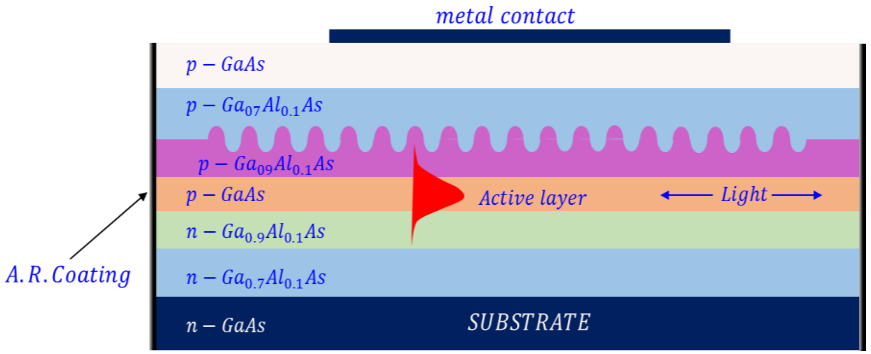
DFB Laser

FP Laser





Single Frequency Lasers: DBR

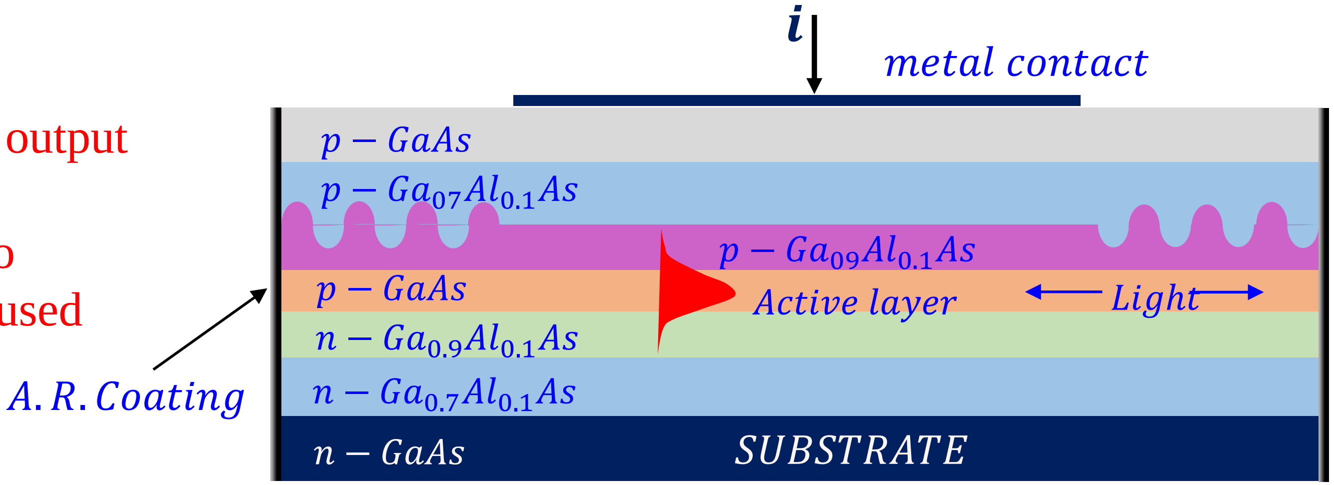


DFB Laser

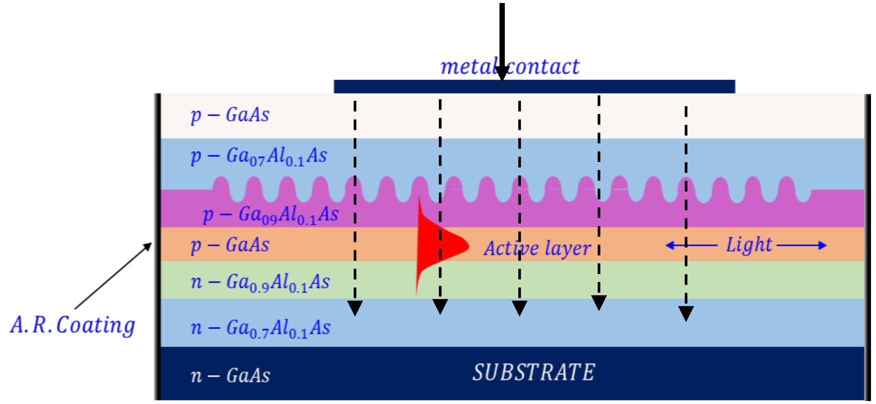
DBR Laser

FP Laser

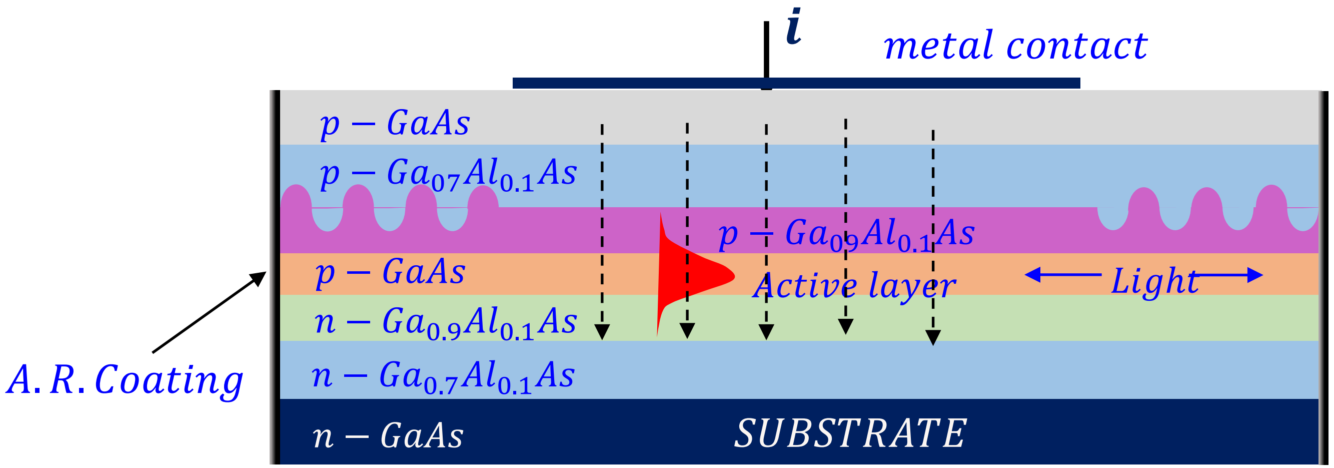
- ❖ More frequency stable at output compared to DFB Laser
- ❖ Comparatively difficult to fabricate DBR mirror so used grating



Single Frequency Lasers: DBR



DFB Laser



DBR Laser

$$\lambda_b = 2n_{eff}\Lambda$$

- wavelength fixed when fabricated the corrugation.
- However refractive index of the medium n_{eff} which is depend on the injection current.
- Depending upon the energy level difference greater and lesser than Eg which determines whether the active medium acts as gain or absorber.

$$Plane\ wave: \ \psi = Ae^{i(\omega t - kz)}\ ;\ k = k_o n$$

$$= Ae^{i\omega t}e^{-ik_o n_r}e^{-k_o n_i z}$$

$$n = n_r - in_i$$

$$n_i > 0 \rightarrow Absorbing$$

$$n_i < 0 \rightarrow Gain$$

$$I = |\psi|^2 = A^2 e^{-2k_o n_i z}$$

$$I(z) = |\psi|^2 = I_0 e^{-2k_o n_i z}$$

QUIZ # 1

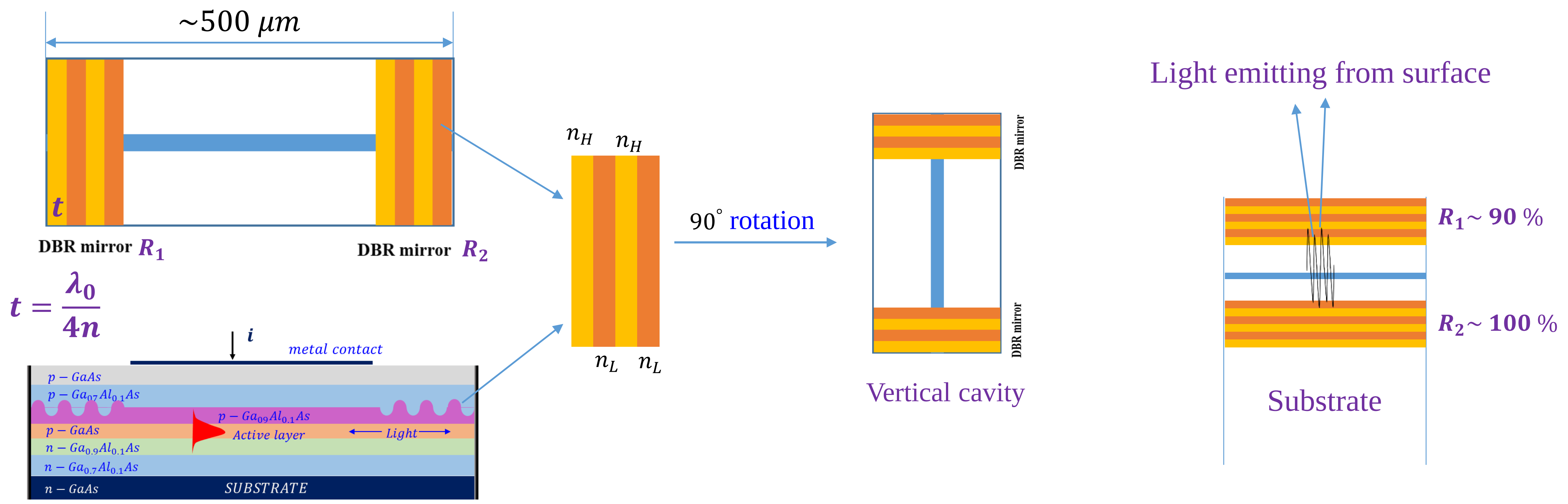
Why are the end facets of a DFB laser chip provided with AR coating

Answer of Quiz # 1

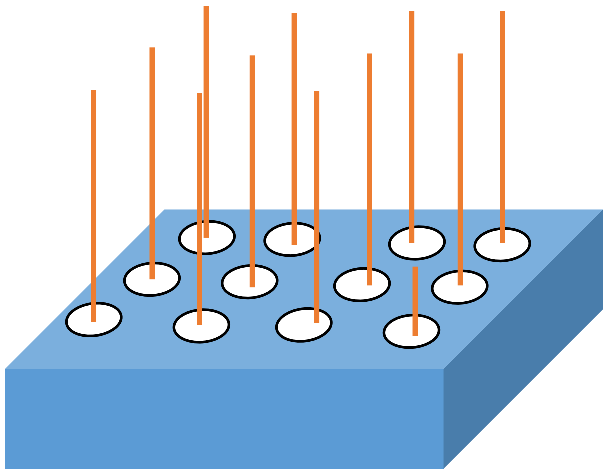
To prevent reflections from the end facets that could lead to the formation of Fabry-Perot cavity/resonances.

Single Frequency Lasers: VCSELs

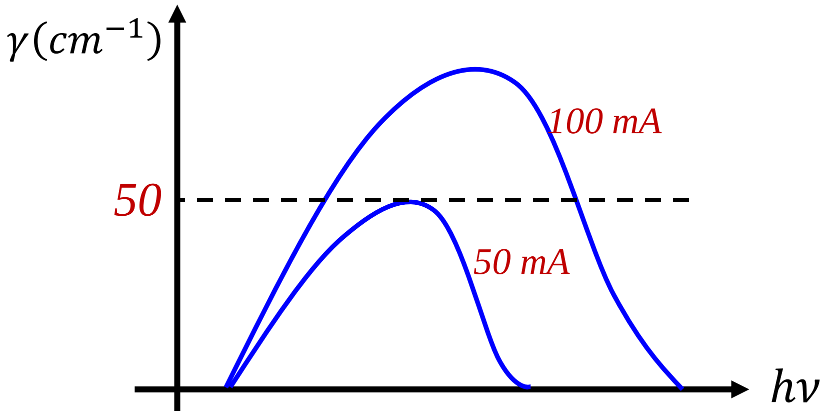
Vertical Cavity Surface Emitting Laser, VCSELs ➡ Variation of DBR Laser



Single Frequency Lasers: VCSELs



Use for High density data interconnects in computer design



For Example:

For equilibrium for resonator

$$\alpha_r = \gamma = \alpha_s + \alpha_m$$

$$\gamma = 50cm^{-1}$$

$$\alpha_s = 10 \sim 50cm^{-1}$$

For minimum values of α_s

$$\alpha_m = 40cm^{-1} = \frac{1}{2l} ln\left(\frac{1}{R_1 R_2}\right)$$

$$\therefore l = \frac{1}{2\alpha_m} ln\left(\frac{1}{R_1 R_2}\right)$$

For normal laser diodes

$$\boldsymbol{R_1 = R_2 \sim 32\%} \textbf{ lower percentage}$$

For VCSELs and DBR

$$\boldsymbol{R_1 = R_2 \geq 90\%} \textbf{ higher value}$$

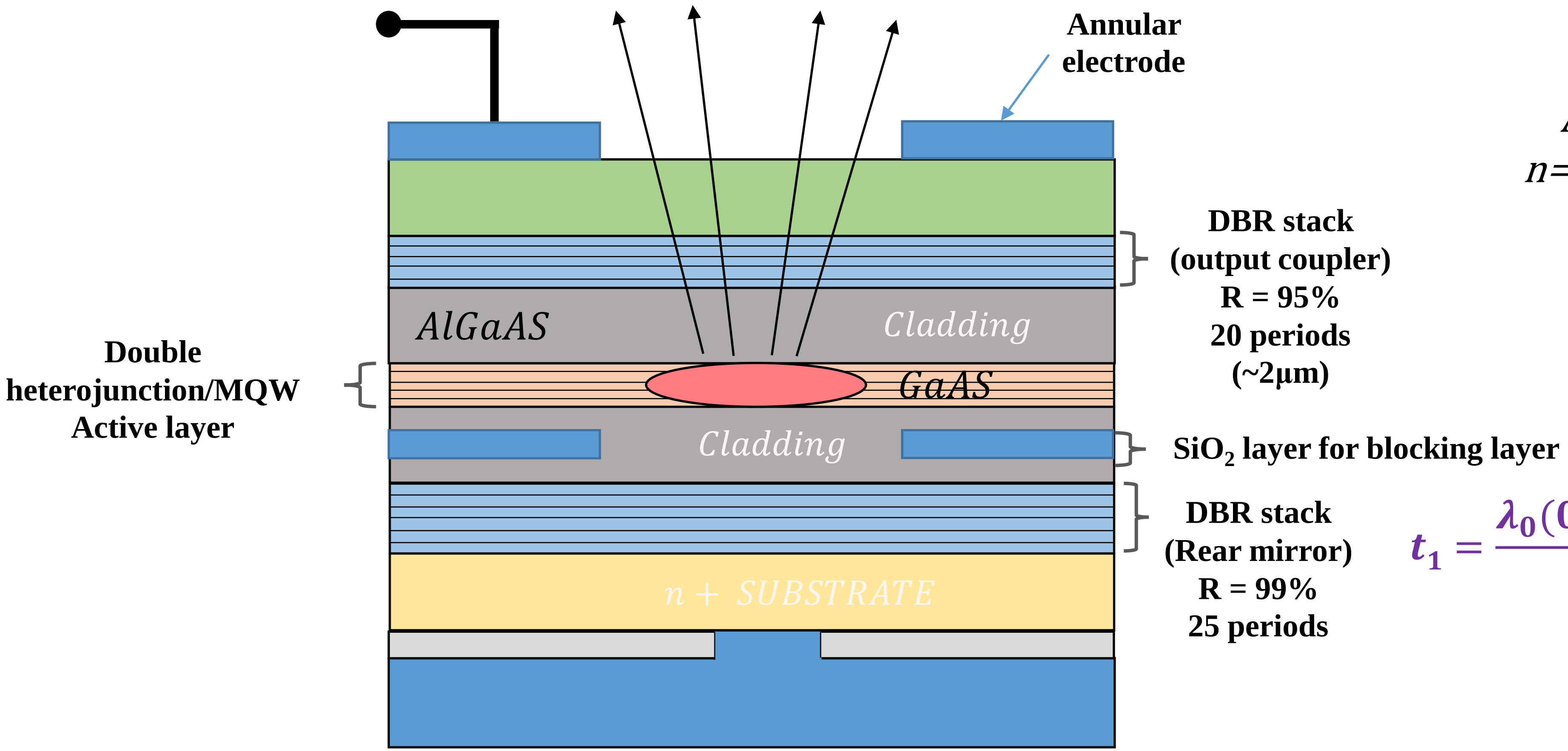
For $\boldsymbol{R_1 = R_2 = R}$

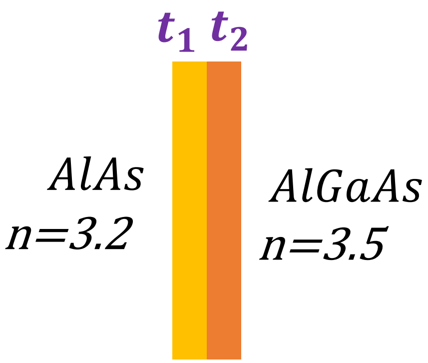
$$\therefore l = \frac{1}{40} ln\left(\frac{1}{R}\right)$$

For different values of R

- R=0.32 → $l \approx 285\ \mu m$
- R=0.9 → $l \approx 10\ \mu m$
- R=0.99 → $l \approx 2.5\ \mu m$
- R=0.998 → $l \approx 0.2\ \mu m$

Single Frequency Lasers: VCSELs





$$t = \frac{\lambda_0}{4n}$$

$$t_1 = \frac{\lambda_0 (0.8\ micrometer)}{4n_1}$$

Vertical cross section of a VCSEL

Single Frequency Lasers: Bragg Reflectors

$$\alpha_r = \alpha_s + \alpha_m \Longrightarrow \gamma_p$$

$10\ cm^{-1}$ $40 cm^{-1}$ $50 cm^{-1}$

For different values of R

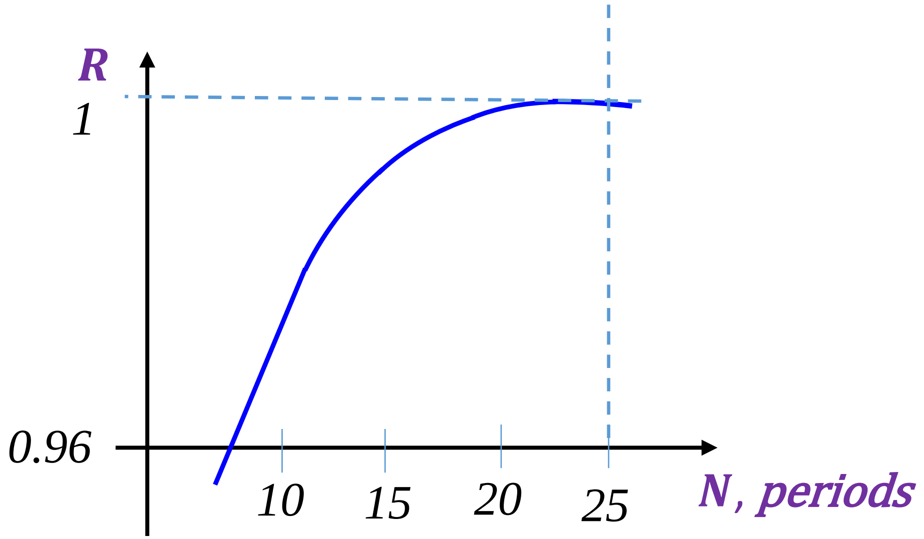
$R=0.32 \longrightarrow l \approx 285\ \mu m$

$R=0.9 \longrightarrow l \approx 10\ \mu m$

$R=0.998 \longrightarrow l \approx 0.2\ \mu m$

Reflectivity of a periodic stack of "high" and "low" index layer is given by

$$R = \left[\frac{1 - \left(\frac{n_L}{n_H}\right)^{2N}}{1 + \left(\frac{n_L}{n_H}\right)^{2N}} \right]^2$$



QUIZ # 2

Why VCSELs have only a single wavelength and greater FSR?

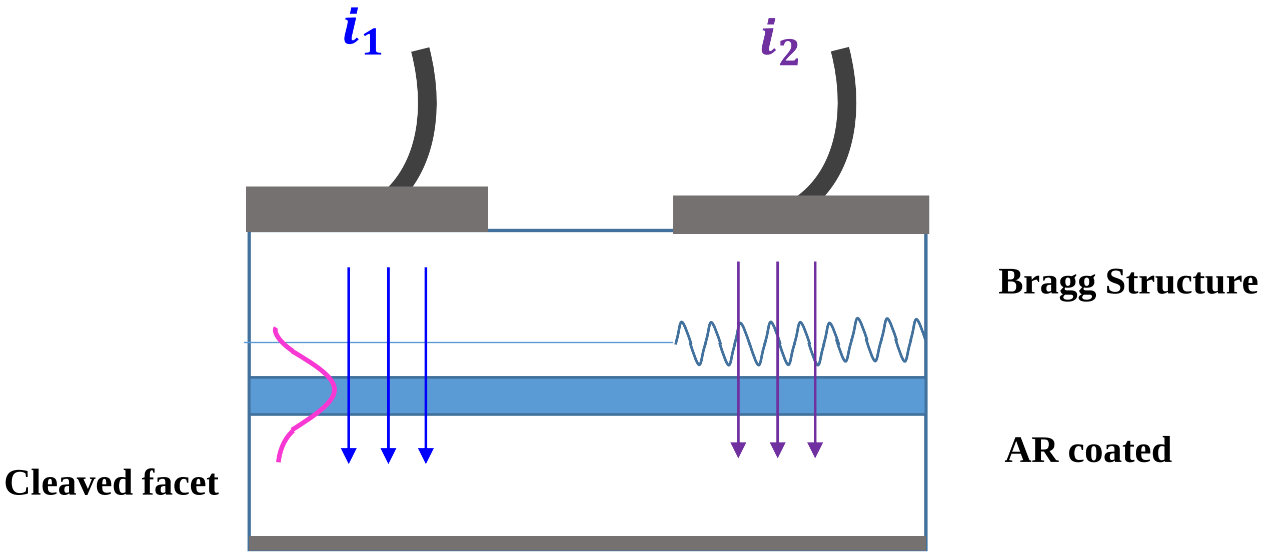
Answer of Quiz # 2

Due to Bragg stacks
Cavity length is small

In VCSELs the cavity length is about 10 μm hence FSR is large and normally the bandwidth of the amplifier cannot cover the more than one longitudinal mode and hence most of the cases VCSELs are SM lasers.

Single Frequency Lasers: Tunable DBR

- two section structure
- Biased separately for two structure
- Frequency selection due to change in Refractive index and Bragg grating frequency
- Tuning range is from 5 nm to 10 nm

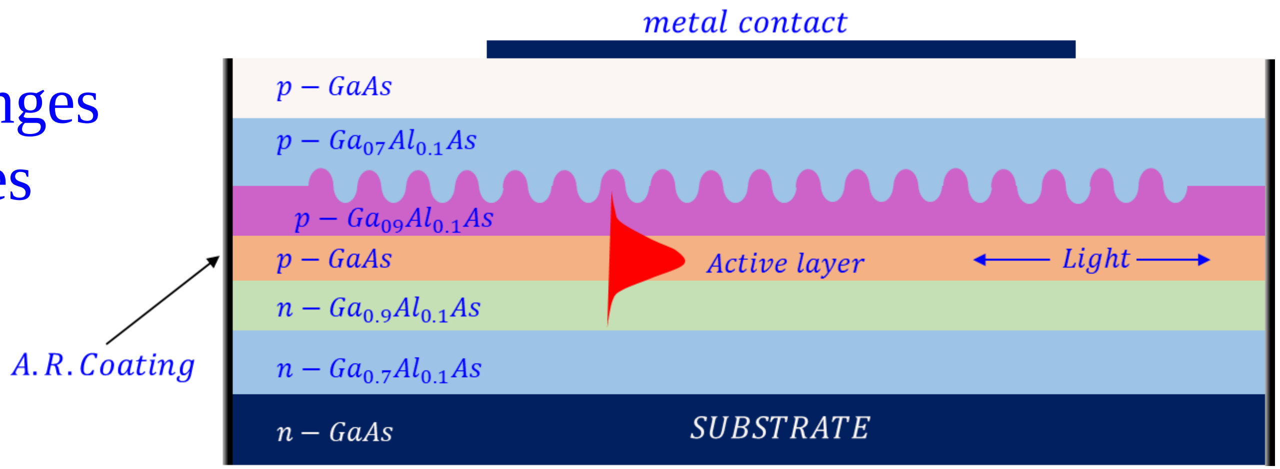


Tunable DBR structure

$$\nu_B \rightarrow \lambda_B = 2n_{eff}\Lambda = \frac{c}{2n_{eff}\Lambda}$$

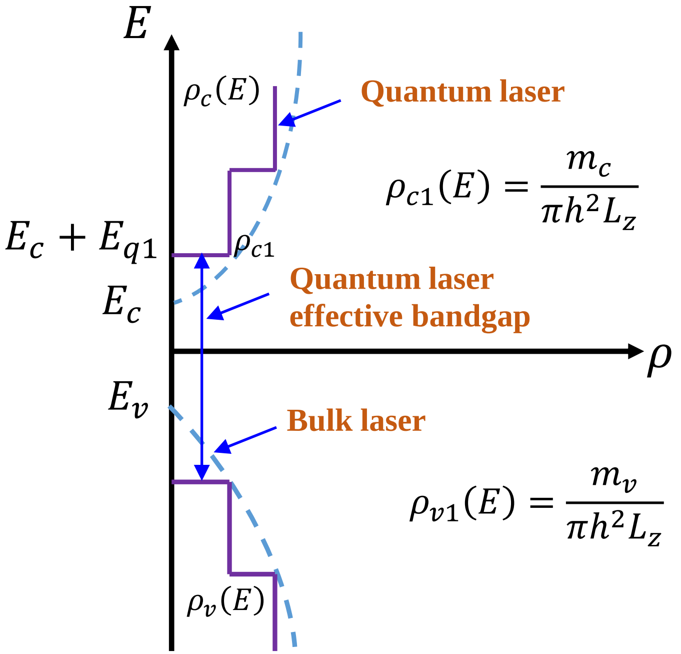
Single Frequency Lasers: Tunable DFB

- Change in Temperature : bandgap changes and hence emitting wavelength changes
- Only small tunable range of 1~3 nm
- Δλ= 0.1nm/oC

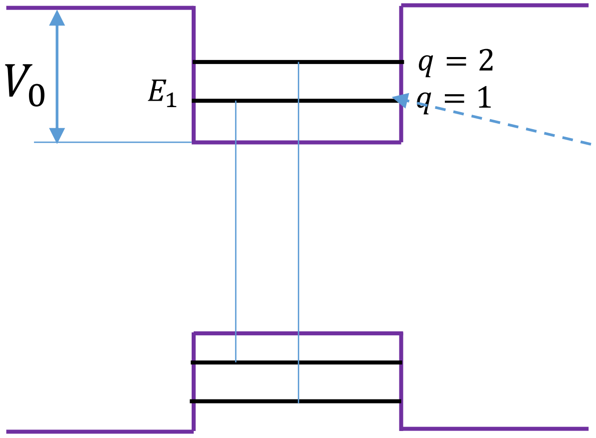


Single Frequency Lasers: Quantum Well Lasers

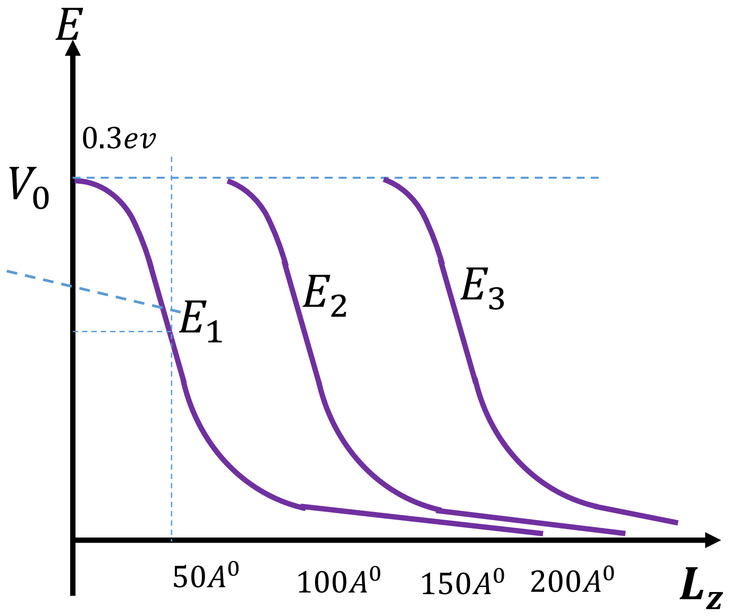
Most of the Lasers have the Quantum Well in Active region



Density of states in Quantum well structures



Energy states in Quantum well structures

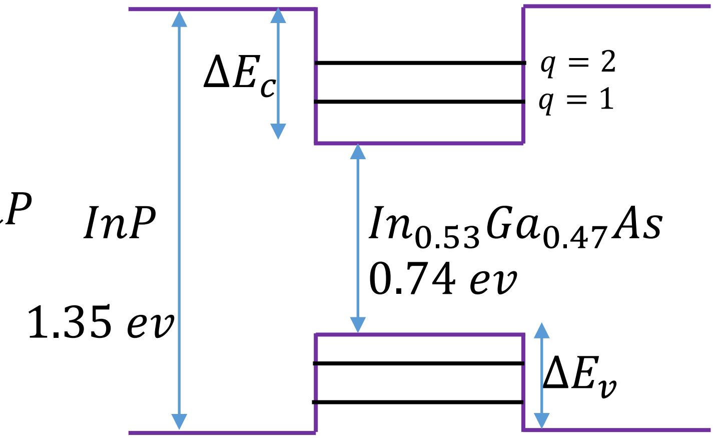


Allowed energy values for different quantum well energy number with quantum well thickness

Single Frequency Lasers: Quantum Well Lasers

For example:-

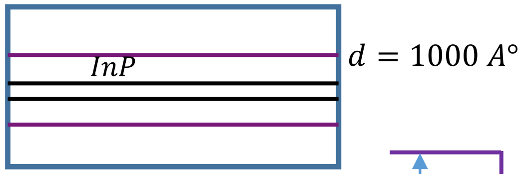
$In_{0.53}Ga_{0.47}As/InP$



$\Delta E_g = 0.61\ ev$

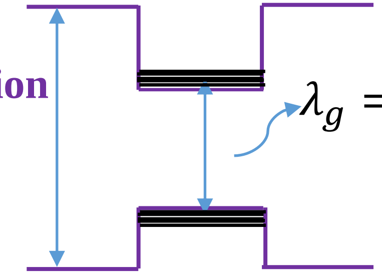
$\Delta E_c \approx 0.65\ \Delta E_g \approx 0.4\ ev$

$\Delta E_v \approx 0.35\ \Delta E_g \approx 0.21\ ev$



Double heterojunction

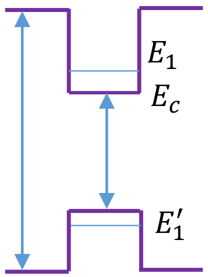
Higher value of debroglie wavelength which is about 10 to 100 $A°$



$$\lambda_g = \frac{1.24}{E_g} = \frac{1.24}{0.74} \approx 1.67\mu m$$

When d is changed to 100 $A°$

Typical value



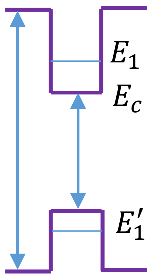
$\Delta E_1 = E_c - E_1 \approx 50\ mev$

$\Delta E_1' \approx 10\ mev$

$$E_g^{eff} = 0.74 + 0.05 + 0.01 = \mathbf{0.8}$$

$$\lambda_g = \frac{1.24}{E_g} = \frac{1.24}{0.8} \approx 1.55\mu m$$

Further decrease to 80 $A°$



$\Delta E_1 \approx 85\ mev$

$\Delta E_1' \approx 15\ mev$

$$E_g^{eff} = 0.74 + 0.085 + 0.015 = 0.84$$

$$\lambda_g = \frac{1.24}{E_g} = \frac{1.24}{0.84} \approx 1.46\mu m$$

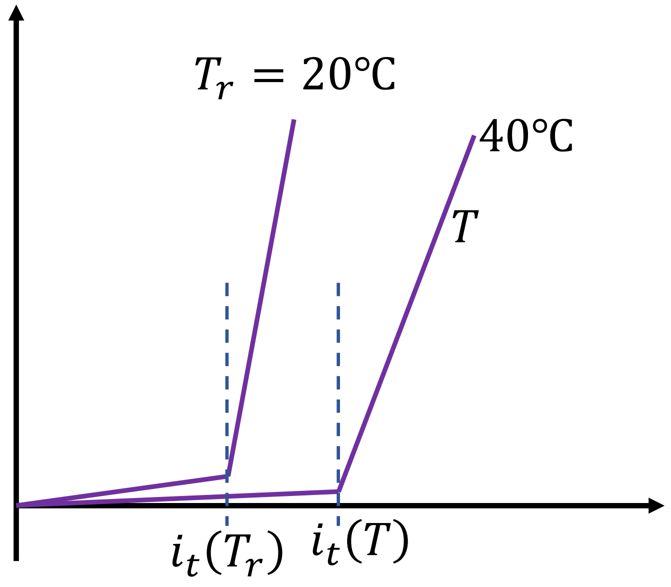
change in small width with change in *higher emission of wavelenth*

Single Frequency Lasers: Quantum Well Lasers

Semiconductor laser double heterojunction laser, where the thickness of active layer is less than de Broglie wavelength of electrons (200 Armstrong to 5 nm which give quantization and gives discrete level of energy)

- ❖ Lower threshold
- ❖ Less sensitive to temperature variation
  - $T_0 \sim 140\ K\ for\ FP\ lasers$
  - $T_0 \sim 400\ K\ for\ QW\ lasers$

$$i_t(T) = i_t(T_r)e^{\left(\frac{T-T_r}{T_0}\right)}$$



larger the value of T_0 less shift in temperature

- ❖ Carrier distribution is less sensitive to the temperature due to the transition level need to be changed as discrete energy level unlike the bulk lasers
- ❖ In QW lasers with increase in temperature there is less non radiative transition hence quantum efficiency, η_i is relatively large and quantum efficiency is less effective with temperature

Single Frequency Lasers: Quantum Well Lasers

Gain coefficient

$$\gamma = \alpha_a\left(\frac{\Delta n}{\Delta n_T} - 1\right) = \alpha_a\left(\frac{J}{J_T} - 1\right)$$

$$\gamma = \frac{\lambda^2}{8\pi\tau}\rho(v)f_g(v)$$

Density of states in Quantum well structures

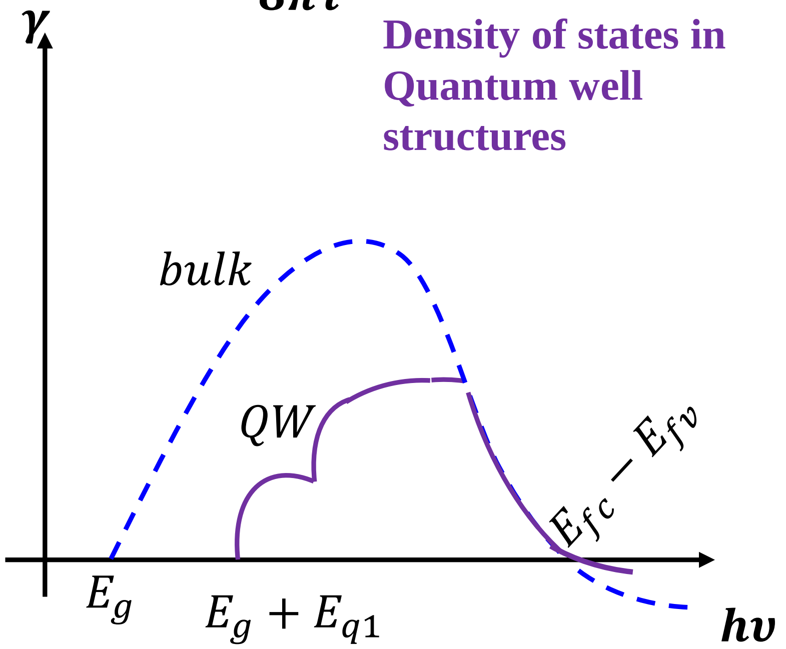


Fig. 1 Gain as a function of Energy

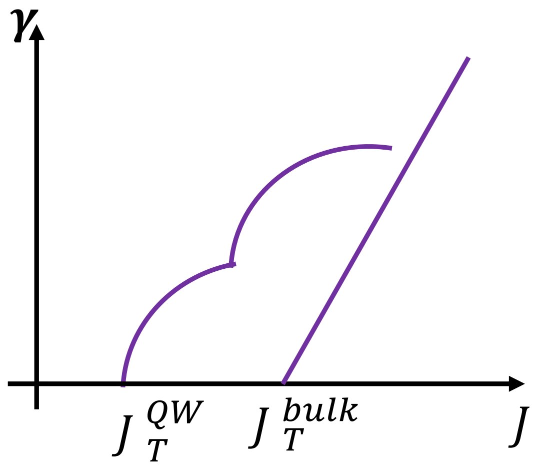
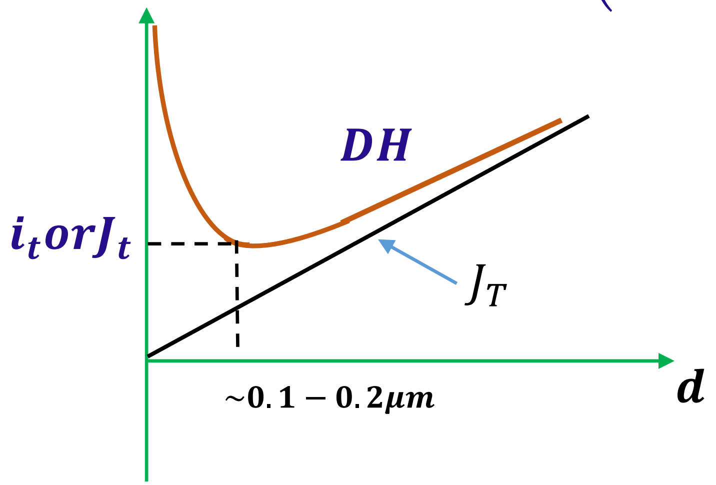


Fig. 2 Gain as a function of current density

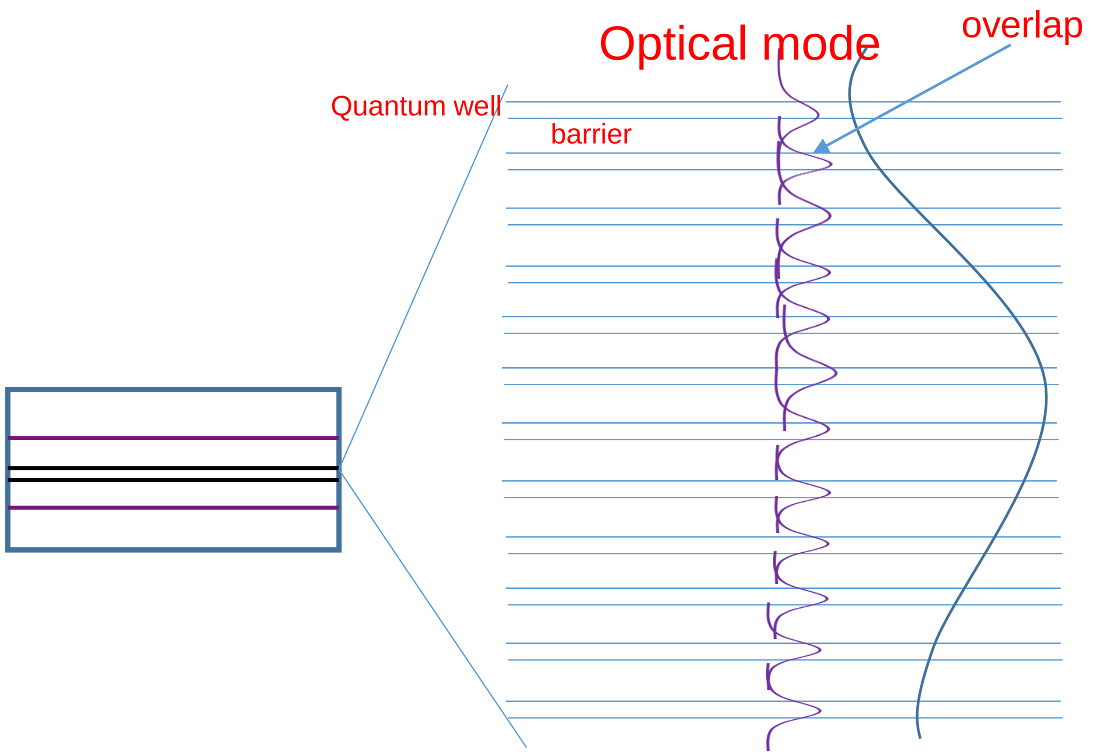
Confinement factor: $J_t = J_T\left(1 + \frac{\alpha_r}{\Gamma\alpha_a}\right)$



For QW lasers

- d is less then we expect threshold to go which is because of confinement factor Γ in heterojunction
- In QW lasers although the confinement factor is small gain is much higher for QW well and quantum efficiency is very high and $f_g(v)$ increase rapidly
- Net effect even we have less value of d, less the threshold current

Single Frequency Lasers: MQW



MQW lasers

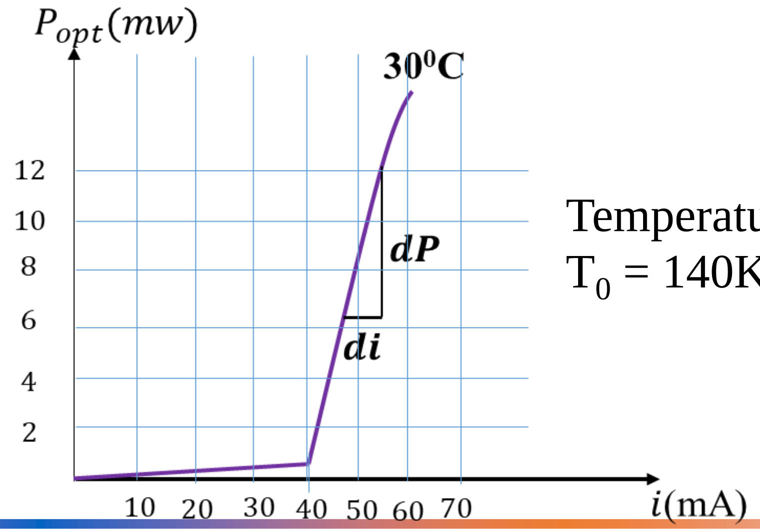
- Active level comprises of multiple quantum well structures comprises of identical potential wells and barriers.
- Barrier thickness is sufficiently large so that electron wave function does not interact with each other.
- Identical not interacting wells
- Enhancement of effective gamma with one overall optical field
- Higher optical output power as overall active area increases
- Typical 2 to 6 QW layer

Assignment# 03

1. **Why DBR laser have better frequency stability compared to the DFB laser?**
2. **Why the reflectivity R is chosen higher value in VCSELs?**
3. **Why the coupling efficiency of VCSELs is better than Fabry perot lasers?**

4. For the given typical parameter of laser diode as follows, what is the transparent current at T=30^{o}C and T=40 ^{o}C. Also, plot the graph for $P_{optical}$ when the temperature is raised to 40^{o}C showing threshold current.

Scattering loss due to inhomogeneity = 20 cm^{-1};
Absorption co-efficient= 600 cm^{-1};
Length of the cavity= 285 μm;
Reflectivity of cavity mirrors are 32%



Temperature coefficient
T_0 = 140K

Any Queries