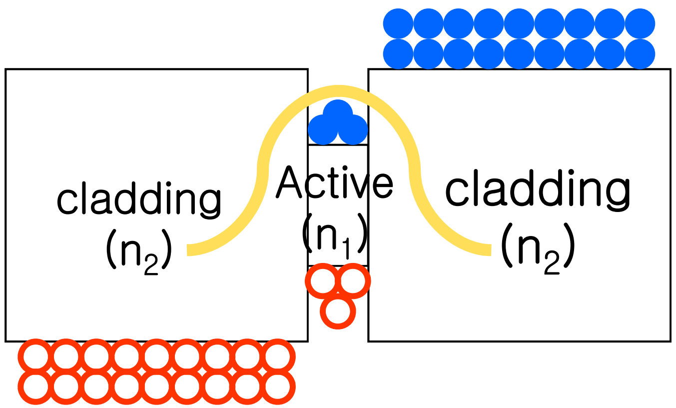
Lect. 23: Single-Mode Semiconductor Lasers

Two conditions for lasing: (1) $\Gamma g_{\mathrm{th}} = \alpha_{\mathrm{m}} + \alpha_{\mathrm{int}}$ and (2) $\dfrac{\lambda}{n_{\mathrm{eff}}} = \dfrac{2L}{m}$

There can be several lasing modes: several λ's satisfying above conditions.

– Multiple values for n_{eff} if there are multiple waveguide modes



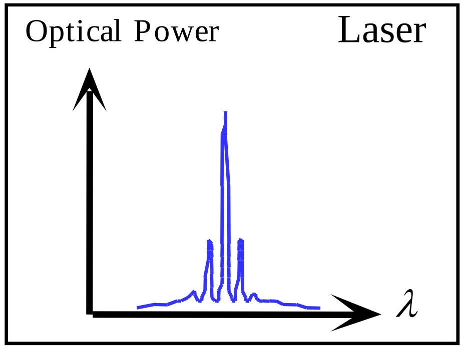
Different modes have different n_{eff}

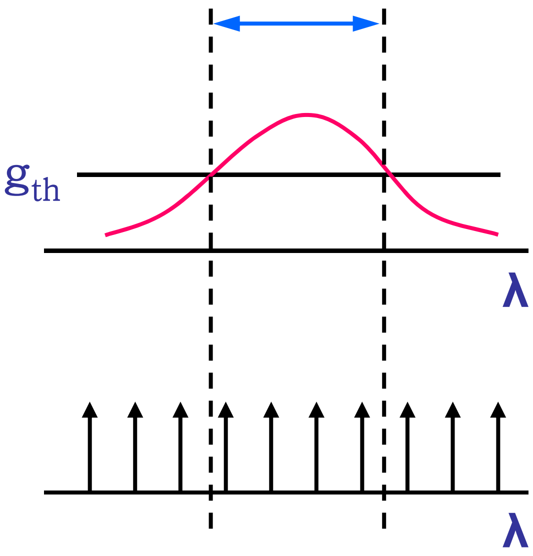
=> Design for single guided mode.

TE, TM modes?

Lect. 23: Single-Mode Semiconductor Lasers

- Multiple cavity modes





Mode separation

From $e^{-j2nk_0L} = 1 \Rightarrow 2n_{\text{eff}} k_0 L = 2m\pi$

$$\Delta(n_{\text{eff}} k_0)L = \pi \;=>\; \Delta(n_{\text{eff}} k_0) = \frac{\pi}{L}$$

$$\lambda = n_{eff} \frac{2\pi}{k_0} \quad \therefore \Delta\lambda = \frac{\delta\lambda}{\delta k_0}\Delta k = -n_{eff}\frac{2\pi}{k_0^{\;2}}\Delta k = -\frac{\lambda^2}{2n_{eff}L}$$

$$\frac{\lambda}{n_{\text{eff}}} = \frac{2L}{m} \text{ for } g(\lambda) > g_{\text{th}}$$

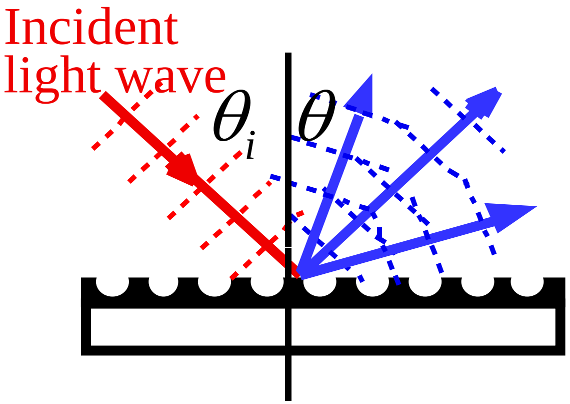
With typical semiconductor lasers with cleaved facets, Δλ is less than gain bandwidth => multi lasing modes

➔ Fabry-Perot laser

Lect. 23: Single-Mode Semiconductor Lasers

Single-mode laser for long-distance, high-speed optical communications?

Use another type of mirror: Grating



$$d\left(\sin\theta - \sin\theta_i\right) = m \cdot \lambda$$

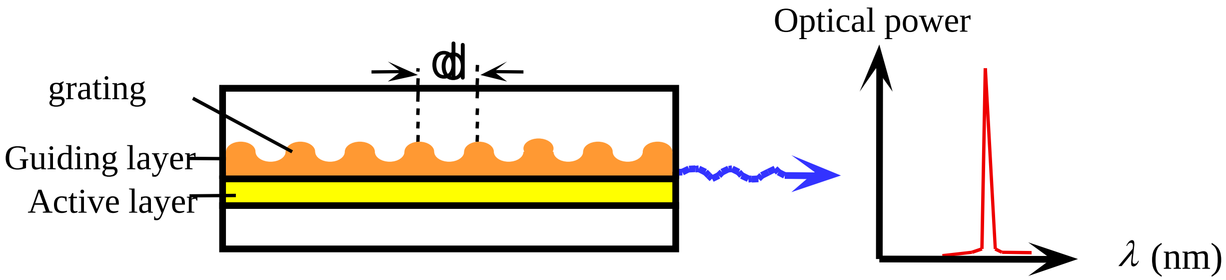
For $\theta_i = 90^\circ$ and $\theta = -90^\circ$,

$$d = m\frac{\lambda}{2}$$

Lect. 23: Single-Mode Semiconductor Lasers

How to implement diffraction grating within semiconductor laser?

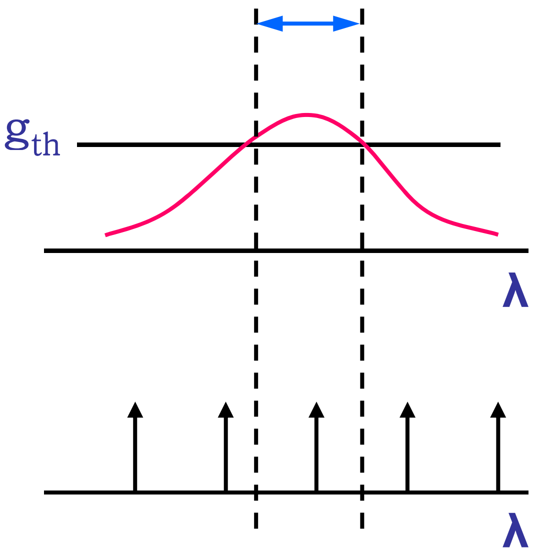
Distributed Feedback (DFB) Laser



$$d = m\frac{\lambda}{2n_{\text{eff}}} \quad \text{(typically m=1)}$$

Lect. 23: Single-Mode Semiconductor Lasers

Another approach: Make L very small so that $\Delta\lambda$ larger than gain bandwidth



gain bandwidth: in the order of 10nm

λ : $1.5\mu m$

n_{eff} : 3.5

$L \sim 30\mu m$;

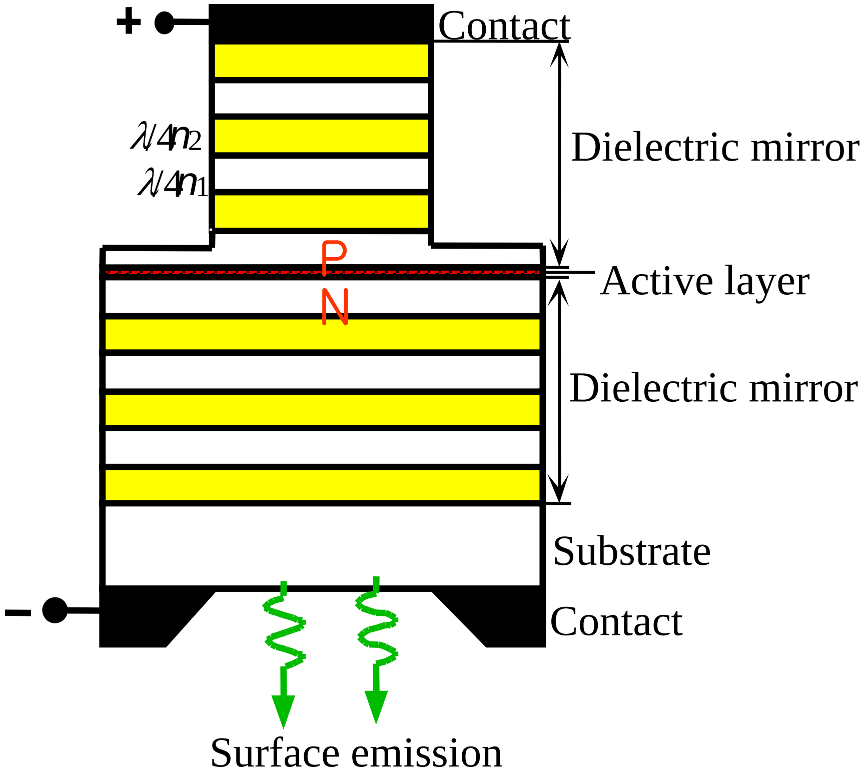
Not easy to fabricate by cleaving

$$|\Delta\lambda| = \frac{\lambda^2}{2n_{eff}L}$$

From $\alpha_m = \frac{1}{L}\ln\frac{1}{R}$, too much mirror loss

Lect. 23: Single-Mode Semiconductor Lasers

Solution: Very short cavity vertical lasers with very high reflectivity mirrors
(VCSEL: Vertical Cavity Surface Emitting Laser)



In semiconductor fabrication, vertical thickness can be very precisely controlled.

Dielectric mirror can have high reflectivity approaching R=1.

From $\alpha_m = \frac{1}{L}\ln\frac{1}{R}$,

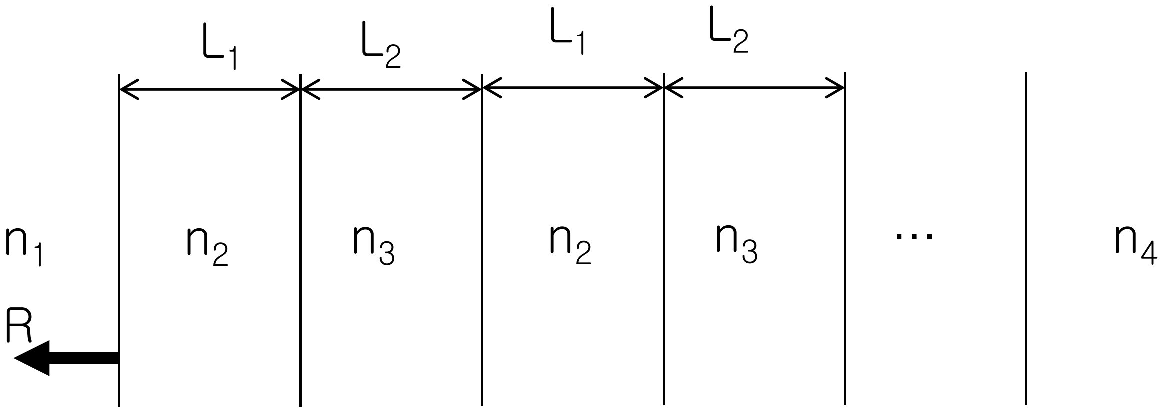
α_m can be made small if R approaches 1.

VCSELs are cheap because it is easy to make.

Lect. 23: Single-Mode Semiconductor Lasers

Review: High-Reflection Coating => Dielectric mirror

Repeat the quarter-wavelength pair m times.



$$R = \left(\frac{n_1 - \left(\frac{n_2}{n_3}\right)^{2m} n_4}{n_1 + \left(\frac{n_2}{n_3}\right)^{2m} n_4} \right)^2$$

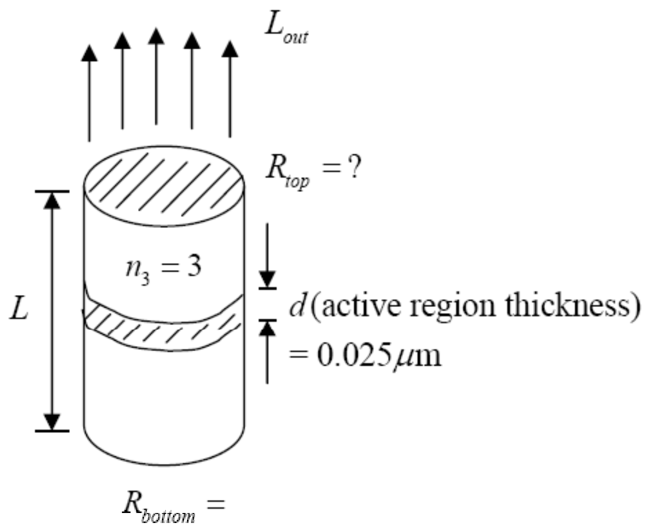
If $n_2 > n_3$, $R \approx \left(\frac{-(n_2/n_3)^{2m} n_4}{+(n_2/n_3)^{2m} n_4} \right)^2 = 1$

If $n_2 < n_3$, $R \approx \left(\frac{n_1}{n_1} \right)^2 = 1$

Lect. 23: Single-Mode Semiconductor Lasers

Homework (Optional): Prob. 1 in 2002 Final

<u>Prob. 1</u> We want to design a circular VCSEL (Vertical Cavity Surface Emitting Laser) lasing at 1um whose structure is shown below. The values for important laser and material parameters are also given. For simplicity, assume there is no internal loss, the optical confinement factor is 1, the refractive indices for both active region and claddings are 3 (n_1 = 3), and the bottom mirror has the reflectivity of 1.



gain at 1μm

$g = a(n - n_0)$

$a : 2.5\times10^{-16} / cm^2$

$n_0 : 10^{18} / cm^3$

τ (carrier lifetime) = 1nsec

radius: 5μm

Lect. 23: Single-Mode Semiconductor Lasers

Homework (Optional): Prob. 1 in 2002 Final

(a) Determine the minimum possible value for L, the laser cavity length.

(b) We want the VCSEL to have the threshold current of 1mA. What is n_{th}, the threshold carrier density in cm^{-3}, and g_{th}, threshold gain in cm^{-1}?

(c) What is the top mirror reflectivity in order to realize (b)?

(d) The top mirror can be realized by stacking up two materials: one with n_2 = 2.2 and the other with n_3 = 1.1. What is the layer thickness for n_2 and n_3?

(e) Which layer should be stacked first, layer with n_2 or n_3? Why? Assume the active region is in the middle of the laser cavity.

(f) What is the minimum number of staked layers required? Assume the laser is located in the vacuum.