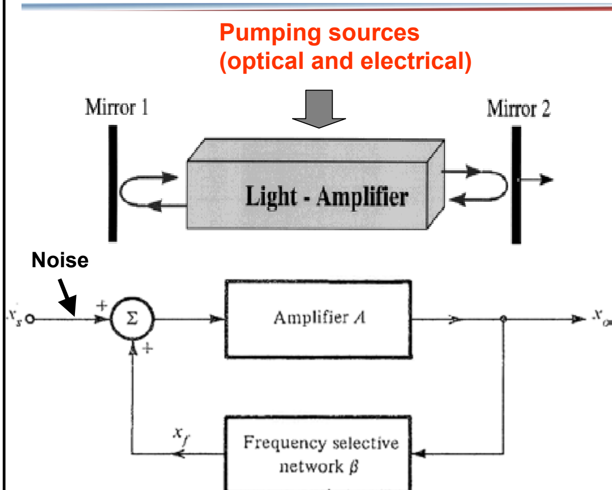
Semiconductor Lasers

Class: Integrated Photonic Devices
Time: Fri. 8:00am ~ 11:00am.
Classroom: 資電206
Lecturer: Prof. 李明昌(Ming-Chang Lee)

Principles of Laser Operation

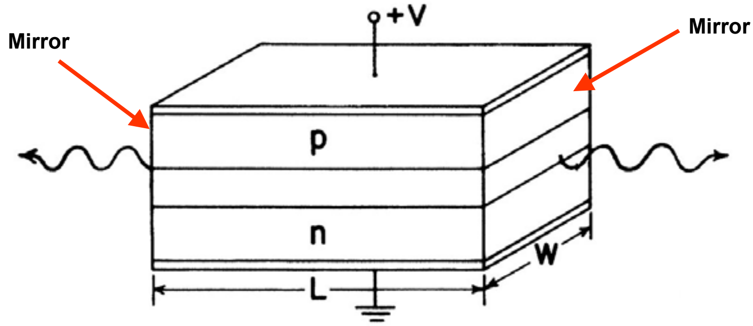


The basic structure of a sinusoidal oscillator.

Laser = Gain medium + Cavity

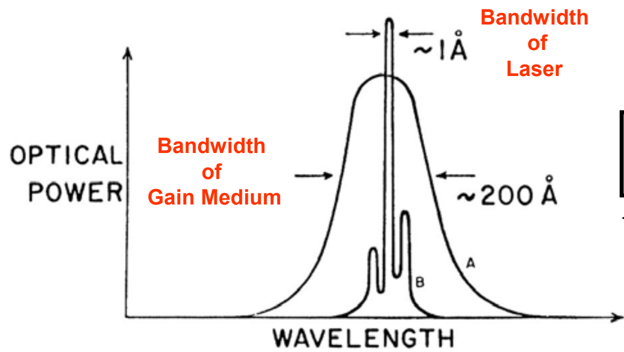
- **Amplifier is the gain medium (population inversion)**
- **Positive feedback is provided by a resonator (Fabry-Perot Etalon, Bragg Grating, Ring Resonator,…)**
- **Initial stimulus comes from spontaneous emission (noise)**
- **Saturation is reached when gain = loss**

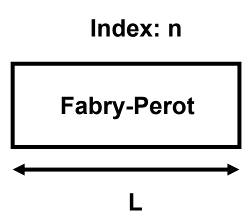
Basic Structure of p-n Junction Laser Diode



- Epitaxial growth of a p-type layer on an n-type substrate
- GaAs, $Ga_{(1-x)}Al_xAs$, $Ga_xIn_{(1-x)}As_{(1-y)}P_y$ are often used for different wavelengths
- Ohmic contacts
- Two parallel end faces are used as partially reflected mirrors

Fabry-Perot Etalon for Optical Feedback

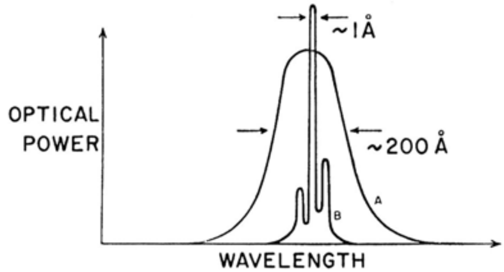


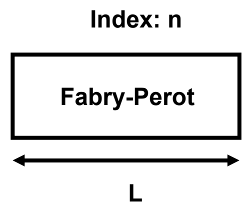


- Only the fundamental longitudinal modes have high quality factors (low loss) which can be utilized for laser modes
- The mode number m is given by the number of half-wavelengths

$$m = \frac{2Ln}{\lambda_0}$$

Fabry-Perot Etalon for Optical Feedback





The mode spacing (free spectrum range) is determined by

$$\frac{dm}{d\lambda_0} = -\frac{2Ln}{\lambda_0^2} + \frac{2L}{\lambda_0}\frac{dn}{d\lambda_0}$$

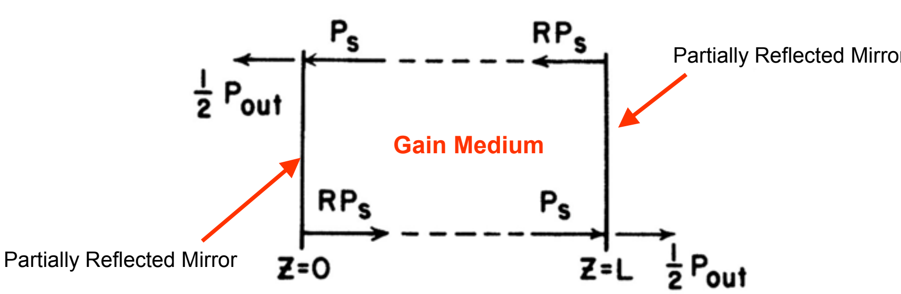
The mode spacing d λ_0 is given by taking dm = -1

group index

$$d\lambda_0 = \frac{\lambda_0^2}{2L\boxed{(n - \lambda_0 \frac{dn}{d\lambda_0})}}$$

- **Usually several longitudinal modes will coexist. (multiple modes)**

Lasing Threshold Conditions (Threshold Current)

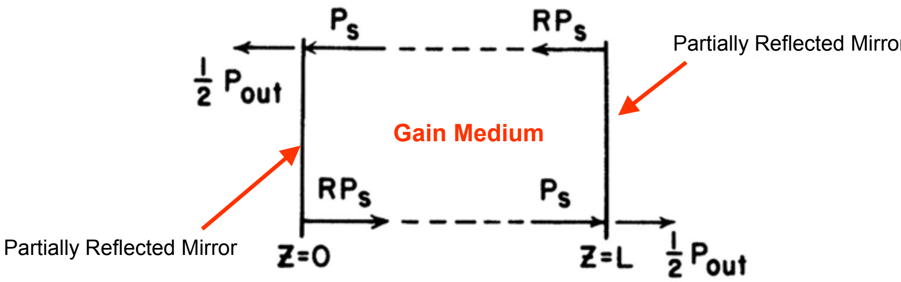


- **For oscillation (lasing), the net gain of a single loop should be equal to 1 (stationary Ps)**

$$\boxed{\textbf{Loss = Gain}}$$

- **Loss is due to propagation loss (scattering, absorption) and optical transmission through mirror**
- **Gain is due to population inversion at the p-n junction**

Lasing Threshold Conditions (Threshold Current)

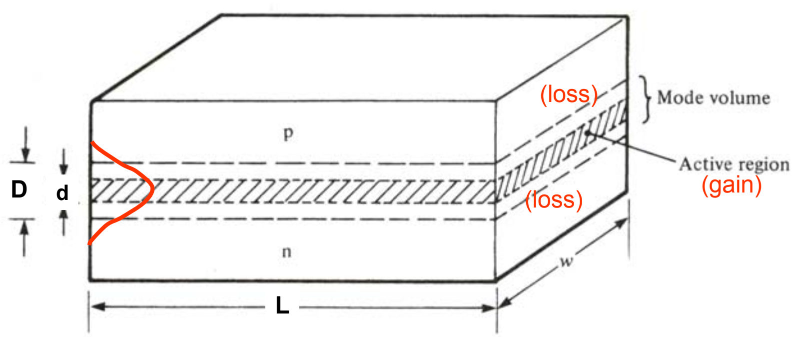


Power variation during propagation: $P = P_s \exp(g\frac{d}{D} - \alpha)Z$

Gain

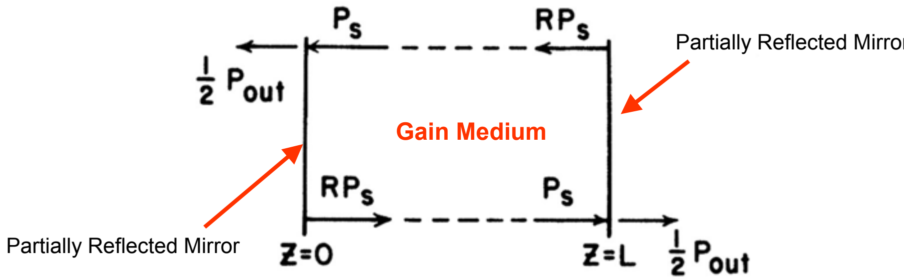
Loss

Transverse Spatial Energy Distribution in a Diode Laser



- **The photon distribution extends or spread into the inactive regions on each side of the junction (optical mode width)**
- **The index is a little high in depletion region**
- **only a fraction d/D remain in the active region and can generate additional photons by stimulated emission**

Lasing Threshold Conditions (Threshold Current)



To maintain the loop gain equal to 1,

$$P_s = RP_s \exp(g\frac{d}{D} - \alpha)L \quad \textbf{or} \quad \ln\frac{1}{R} = \left(g\frac{d}{D} - \alpha\right)L$$

where R is the reflectance. Thus,

$$g\frac{d}{D} = \alpha + \frac{1}{L}\ln\frac{1}{R}$$

Lasing Threshold Conditions (Threshold Current)

The gain coefficient g is related to the injected current density of holes and electrons. It can be given by

$$\boxed{g = \frac{\eta_q \lambda_0^2 J}{8\pi e n^2 d \Delta\nu}}$$

η_q : internal quantum efficiency

λ_0 : vacuum wavelength emitted

n : index of refraction at λ_0

$\Delta\nu$: linewidth of spontaneous emission

e : electron charge

d : thickness of active region

J : injected current density

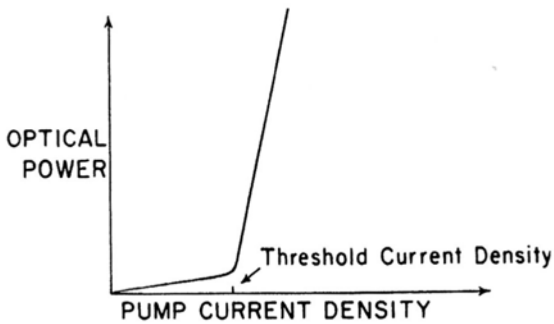
Therefore, the threshold condition for lasing is

$$\underbrace{\frac{\eta_q \lambda_0^2 J_{th}}{8\pi e n^2 \Delta\nu D}}_{\text{effective gain per pass}} = \alpha + \underbrace{\frac{1}{L}\ln\frac{1}{R}}_{\text{effective loss per pass}} \quad \textbf{or} \quad \boxed{J_{th} = \frac{8\pi e n^2 \Delta\nu D}{\eta_q \lambda_0^2}\left(\alpha + \frac{1}{L}\ln\frac{1}{R}\right)}$$

Lasing Threshold Conditions (Threshold Current)

The threshold current is that which is necessary to produce just enough gain to overcome the losses

Note that, from the standpoint of threshold, the light output of laser at the end faces must be counted as a loss.



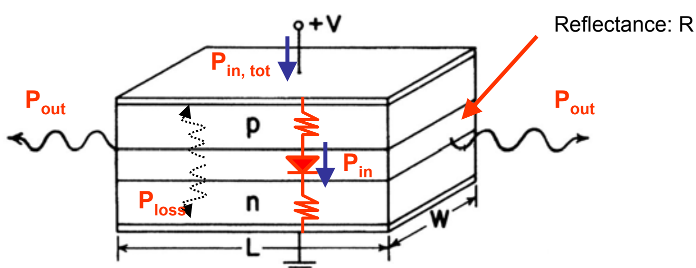
$$\frac{1}{L}\ln\left(\frac{1}{R}\right)=\frac{1}{L}\ln\left(\frac{1}{1-T}\right)$$
$$=\frac{1}{L}\left(T-\frac{T^2}{2}+\frac{T^3}{3}-\frac{T^4}{4}+\ldots\right)$$

T: transmittance

$$\frac{1}{L}\ln\left(\frac{1}{R}\right)\cong\frac{T}{L}$$

Propagation loss coefficient $\cong \alpha+\frac{T}{L}$

Output Laser Power and Efficiency



The power provided by external injected current should be equal to the emitting laser power as well as loss inside the cavity

The ratio of the emitting power is defined by

$$\eta=\frac{\frac{1}{L}\ln\frac{1}{R}}{\alpha+\frac{1}{L}\ln\frac{1}{R}}$$

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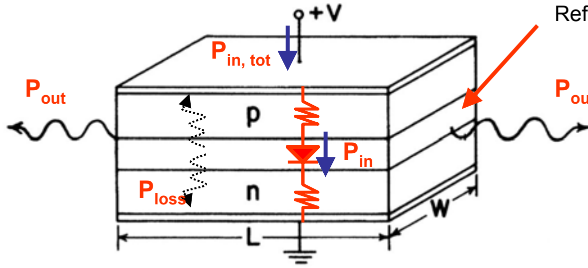
Output Laser Power and Efficiency



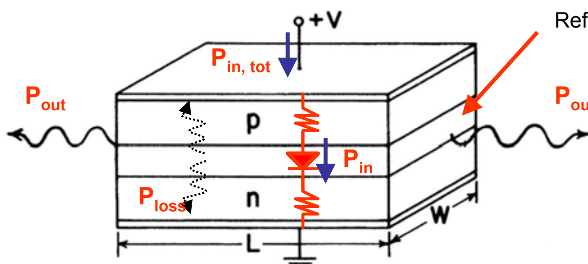
The emitted power is then given by

$$P_{out} = \eta P_{in} = \eta \left[\frac{J}{e} \eta_q \left(L \times W \right) h\nu \right]$$ (P_{out} is power out of both end faces)

which is,

$$P_{out} = \frac{\frac{1}{L}\ln\frac{1}{R}}{\alpha + \frac{1}{L}\ln\frac{1}{R}} \frac{J\eta_q}{e} \left(L \times W \right) h\nu$$

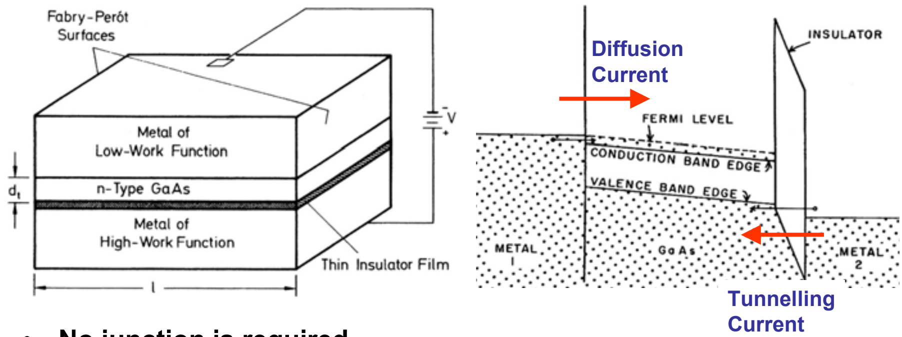
Output Laser Power and Efficiency



The overall power efficiency including the effect of series resistance in the devices is thus given by

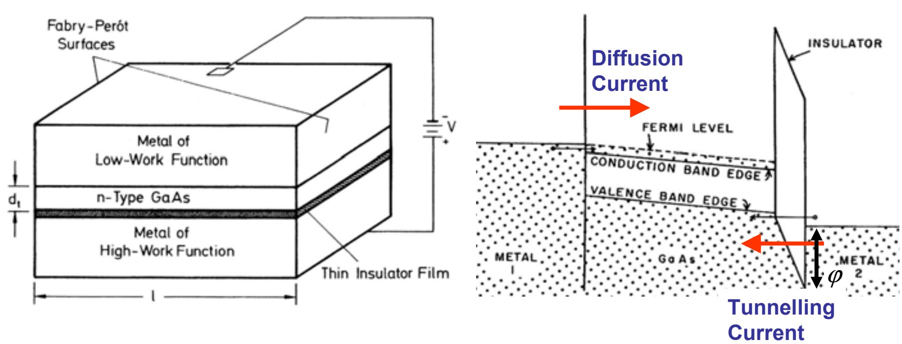
$$\eta_{tot} = \frac{P_{out}}{P_{in,tot}} = \frac{\dfrac{\frac{1}{L}\ln\frac{1}{R}}{\alpha + \frac{1}{L}\ln\frac{1}{R}} \dfrac{J\eta_q}{e} \left(L \times W \right) h\nu}{\dfrac{J}{e} \left(L \times W \right) h\nu + \left[J \left(L \times W \right) \right]^2 R_{series}}$$

Tunnel-Injection Laser



- **No junction is required**
- **Electrons are injected from low-work-function metal by diffusion current**
- **Holes are injected from high-work-function metal by tunnelling current**
- **Holes and Electrons are recombined in the semiconductor region**

Tunnel-Injection Laser



- **The tunnel-injected laser was one of the first of the confined-field type lasers (such as heterojunction lasers)**
- **The optical field is well confined in the semiconductor region due to metal reflection. That is, D=d**