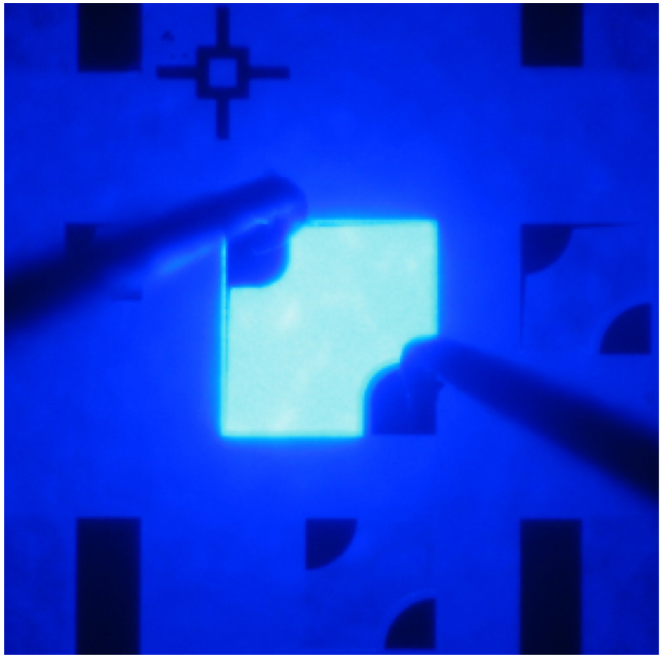
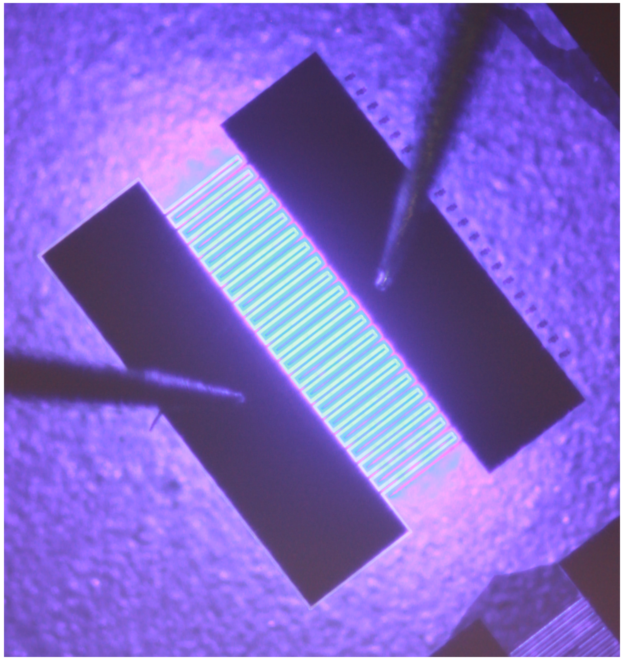
Optoelectronics
ELEC-E3210





Lecture 3

Semiconductor lasers I

P. Bhattacharya: chapters 6&7
J. Singh: chapter 10&11

History

1917 - A.Einstein publishes "On the quantum mechanics of radiation", explaining spontaneous and stimulated emission

1954 - Ch.H.Townes et al.: First maser (= Microwave Amplifier by Stimulated Emission of Radiation) based on ammonia molecules

Charles H. Townes

1959 - G.Gould submits construction sketches for an optical maser for a US patent and introduces the term "laser" (= Light Amplifier by Stimulated Emission of Radiation)

1959 - N.G.Basoc et al.: Proposition for a semiconductor laser

1960 - T.H.Maiman: First laser, consisting of a ruby bar (Cr^{3+}:Al_2O_3) with two parallel faces as resonator and a pulsed flashbulb as optical pumping source, emission wavelength 0.6943 μm

1962 - F.H.Dill; W.E.Howard et al.: Continuous stimulated 0.84 μm emission of GaAs diodes at temperatures of 2 K to 77 K

1963 - H.Kroemer; Zh.I.Alferov and R.F.Kazarinov: Proposition of a double-heterostructure laser diode

History

1968 - Zh.I.Alferov et al.: Pulsed-mode operation of a double-hetero structure laser diode

1970 - Zh.I.Alferov et al.: First continuously emitting double-heterostructure laser diode at room temperature

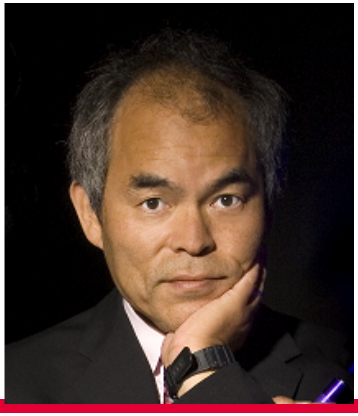
1970 - L.Esaki and R.Tsu: First quantum well structures

1976 - J.Hsieh: Continuously emitting InGaAsP laser diode with an emission wavelength of 1.25 μm

1991 - M.Haase et al.: First short-term operation of a blue-green emitting laser diode on the basis of the II-VI semiconductor ZnSe

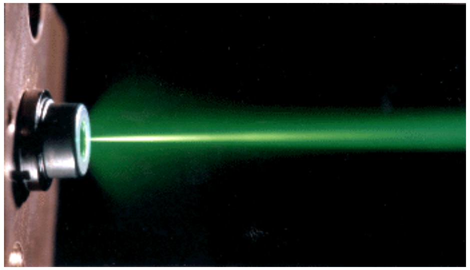
1996 - S.Nakamura: First efficient blue emitting laser diode at room temperature based on GaN

Zhores I. Alferov

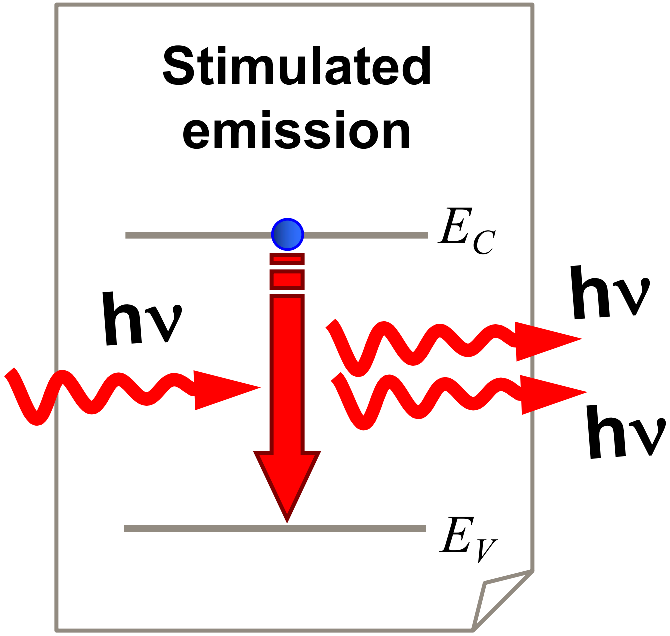


Shuji Nakamura

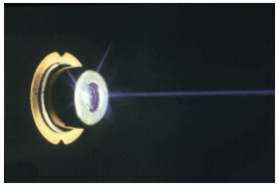
Comparison: LED vs. Laser diode

	LED	Laser
		
Linewidth	> 30 nm	1nm or less
Output power	µW to W	µW to W
Speed	< GHz	up to 100GHz

Stimulated emission



Generates optical gain



Useful in lasers

1. The external photon stimulates radiation with the same frequency it has.
   → **narrow spectral width**

2. All photons propagate in the same direction and contribute to output light
   → high current-to-light conversion efficiency and **high output power**

3. The stimulated light will be well **directed**.

4. External and stimulated photons are in phase → **coherent radiation**

Einstein relations

E_2, N_2

E_1, N_1

Population of the two levels:

$$\frac{N_1}{N_2} = \frac{g_{D1}\exp\left(-E_1/kT\right)}{g_{D2}\exp\left(-E_2/kT\right)} = \frac{g_{D1}}{g_{D2}}\exp\left(\frac{E_2 - E_1}{kT}\right)$$

$g_{D1,2}$ = degeneracies of the levels

$\varphi(\nu)$ = radiation density

B_{12} = Einstein coefficient for absorption

Upward transition rate:

$$r_{12} = N_1\varphi\left(\nu\right)B_{12}$$

Downward transition rate:

$$r_{21} = N_2 A_{21} + N_2\varphi\left(\nu\right)B_{21}$$

Spontaneous emission rate ($N_2 A_{21}$) Stimulated emission rate ($N_2\varphi(\nu)B_{21}$)

B_{21} = Einstein coefficient for stimulated emission

$A_{21} = 1/\tau_{21}$ Einstein coefficient for spontaneous emission

Equilibrium (r_{12}=r_{21}):

Einstein relations

E_2, N_2

E_1, N_1

$$\varphi(\nu) = \frac{A_{21}/B_{21}}{\left(B_{12}N_1/B_{21}N_2\right)-1} = \frac{A_{21}/B_{21}}{\frac{g_{D1}B_{12}}{g_{D2}B_{21}}\exp\left(h\nu_{12}/kT\right)-1}$$

Spectral radiation density for ideal blackbody radiation:

$$\varphi(\nu) = \frac{8\pi n_r^3 \nu^3}{c^3}\frac{1}{\exp\left(h\nu/kT\right)-1}$$

$$B_{12} = \left(\frac{g_{D2}}{g_{D1}}\right)B_{21}$$

$$\frac{A_{21}}{B_{21}} = \frac{8\pi n_r^3 \nu^3}{c^3}$$

To achieve a coherent source in which stimulated emission will dominate, $\varphi(\nu)$ must be increased and N_2 must be made larger than N_1.

→ **Population inversion**

Population inversion and optical gain

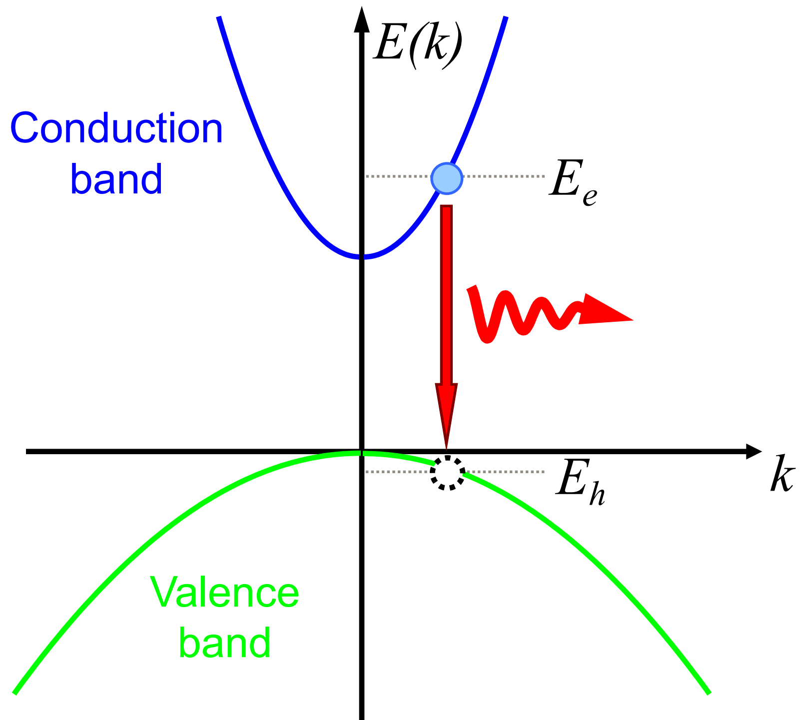
Typically $E_2 > E_1$, $N_1 > N_2$, and absorption $\alpha > 0$ →a medium with **loss**

Wanted: **population inversion** so that $N_2 > N_1$ and $\alpha < 0$ →a medium with **gain!**

A semiconductor is not a two level system..

$$E_e = E_c + \frac{m_r^*}{m_e^*}\left(\ \ \omega - E_g\right)$$

$$E_h = E_v - \frac{m_r^*}{m_h^*}\left(\ \ \omega - E_g\right)$$



Population inversion and optical gain

Emission is proportional to: $f^e \cdot f^h$

Occupation probabilities

Absorption is proportional to: $\left(1-f^e\right)\cdot\left(1-f^h\right)$

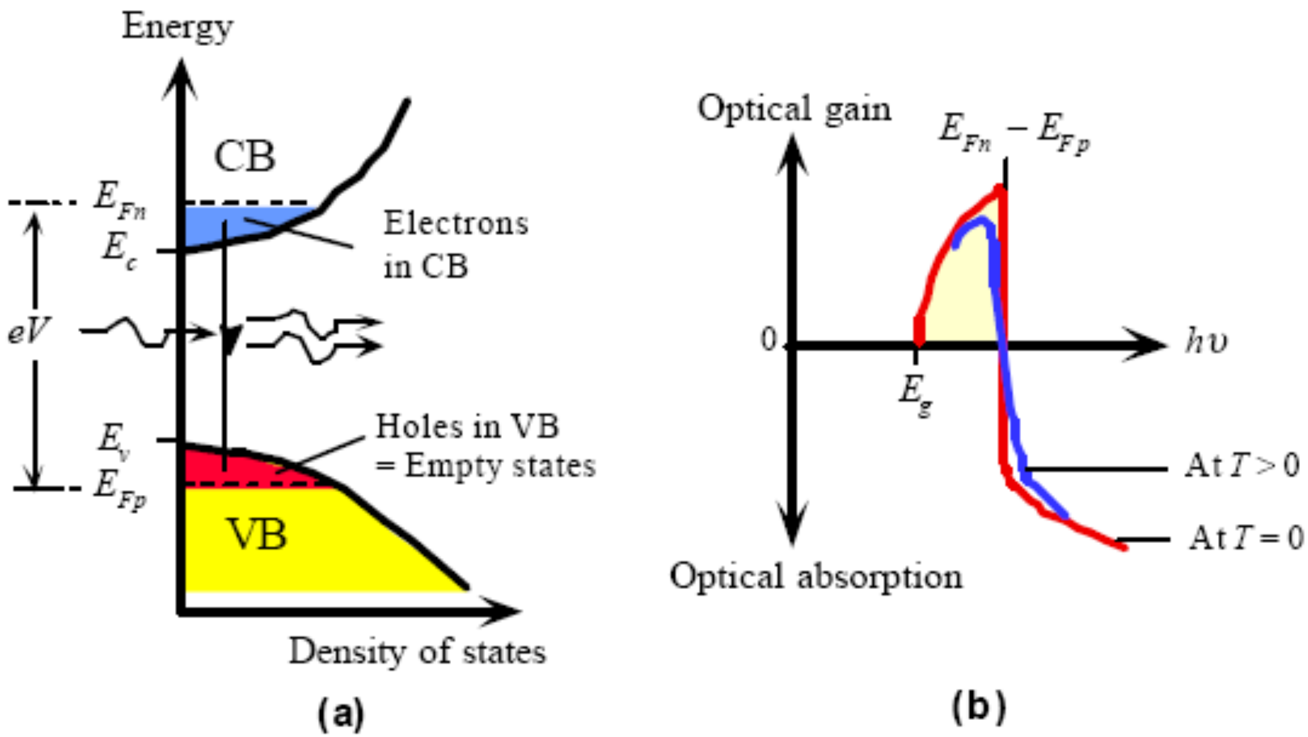
Gain = emission – absorption

$$g(\omega)=\frac{\pi q^2}{m_0^2 c n_r \varepsilon_0}\frac{1}{\omega}\left|a\cdot p_{cv}\right|^2 N_{cv}(\omega)\left[f^e(E_e)+f^h(E_h)-1\right]$$

Gain requires inversion: $f^e(E_e)+f^h(E_h)>1$

The quasi-Fermi levels must penetrate their respective bands!

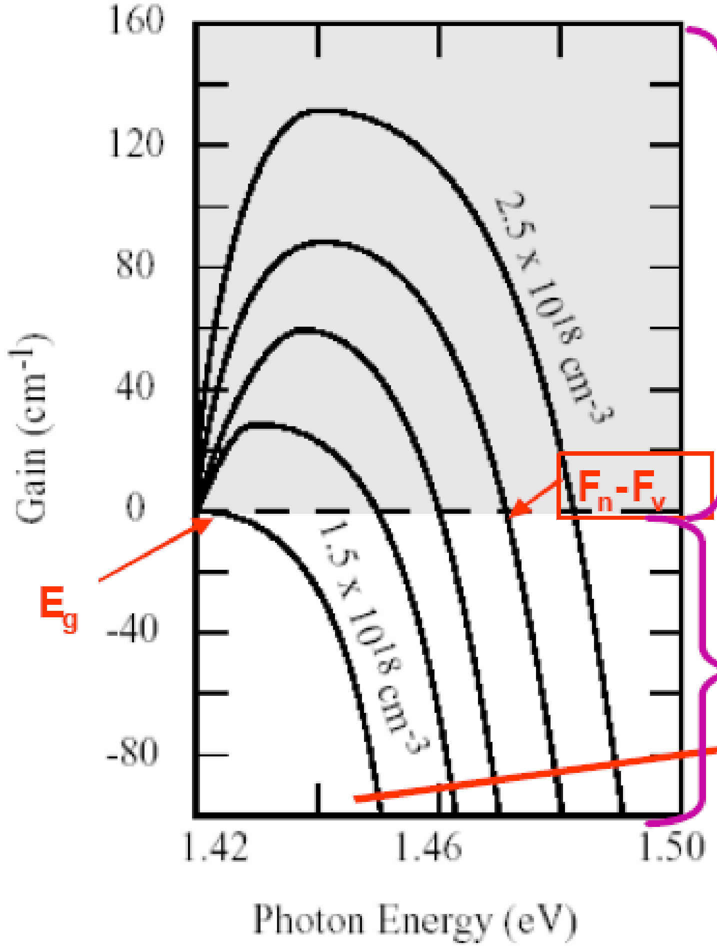
Quasi-Fermi levels and optical gain



(a) The density of states and energy distribution of electrons and holes in the conduction and valence bands respectively at $T \approx 0$ in the SCL under forward bias such that $E_{Fn} - E_{Fp} > E_g$. Holes in the VB are empty states. (b) Gain vs. photon energy.

Gain vs. photon energy

Gain or loss? When?

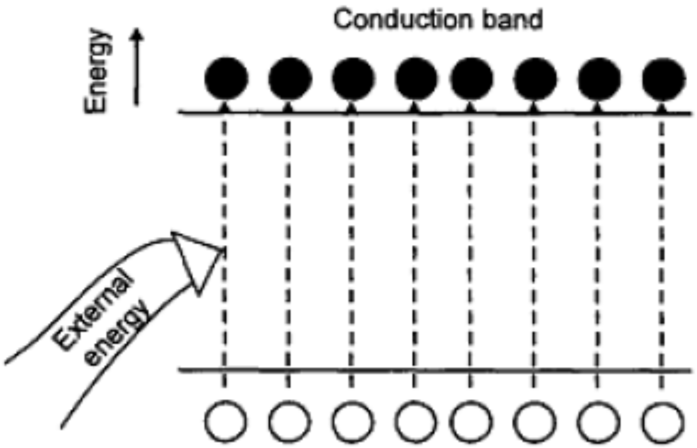


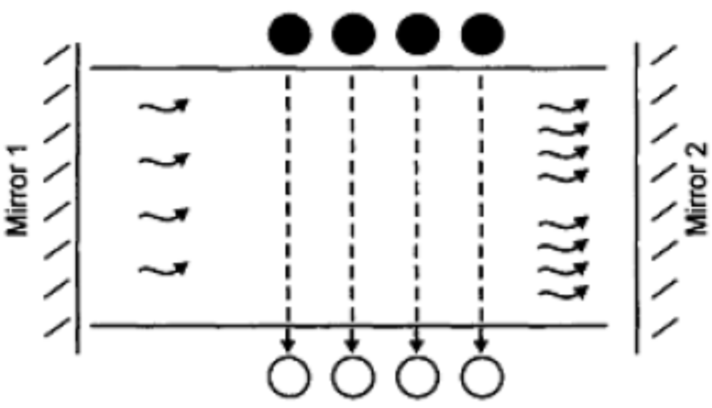
- Photon with energy < E_g cannot excite an electron and hence are transparent => No gain!
- Photon with energy between E_g and F_n-F_v can stimulate recombination => Hence gain!
- Photon with energy > F_n-F_v will only be absorbed! => No gain - only loss!

Increasing carrier density

To get good lasers:
Optimise
Cavity gain
Cavity loss
Mirror loss

Positive feedback and light amplification





We also need **positive feedback** that adds the output (stimulated photons) to the input (external photons). This can be achieved by using mirrors at the end of the active region → a **resonator** is formed and **light amplification** takes place.

For lasing it is essential that the gain in the resonator overcomes the losses due to absorption and transmission at the mirrors.

In semiconductor lasers lasing is achieved **by current injection across a forward-biased junction**. For efficient operation the injected carriers need to be confined in the vicinity of the junction. This is achieved with the use of **heterojunctions**.

Laser diode: requirements

1. Spontaneous emission

(to generate photons)

2. Stimulated emission

*(population inversion needed to create optical amplification = optical gain, **gain must be at least equal to the losses in the medium**)*

3. An optical resonant cavity

*(to achieve a build up of photon density and **coherent radiation** by selective amplification of one frequency usually at the peak of the spontaneous output or luminescence)*

① = LED

①+② = Superluminescent LED

②(+③) = (perfect) Semiconductor Optical Amplifier

LASING = OPTICAL AMPLIFICATION + COHERENCE

Outline

1 **Introduction**

2 **The Fabry-Pérot laser**

3 **Transparency and threshold current**

4 **Heterostructure laser**

5 **Power output and linewidth**

P. Bhattacharya: chapters 6&7
J. Singh: chapter 10&11

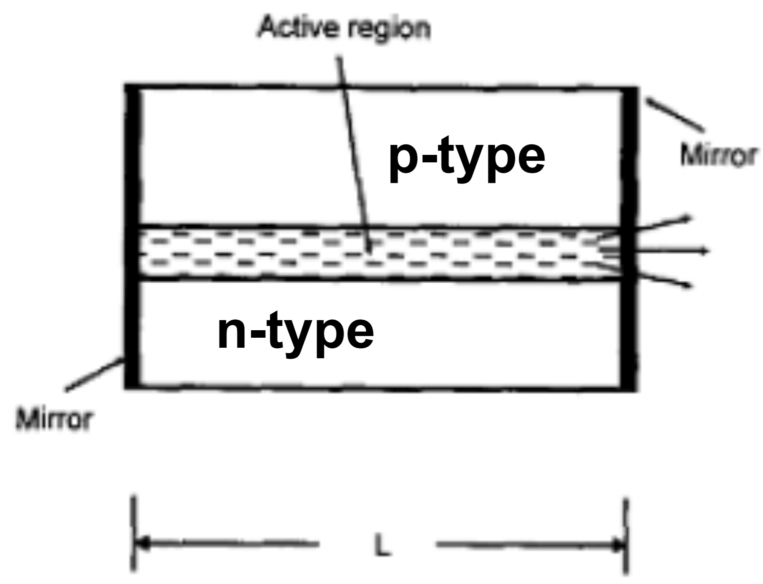
Fabry-Perot laser

- The simplest way to create a resonant cavity is to cleave the end faces of the semiconductor heterojunction. Optical feedback is achieved by multiple reflection at the sample facets
- The device is called a **Fabry-Pérot laser diode** (FP-LD)
- Semiconductor-air interface produces a reflection coefficient at normal incidence of

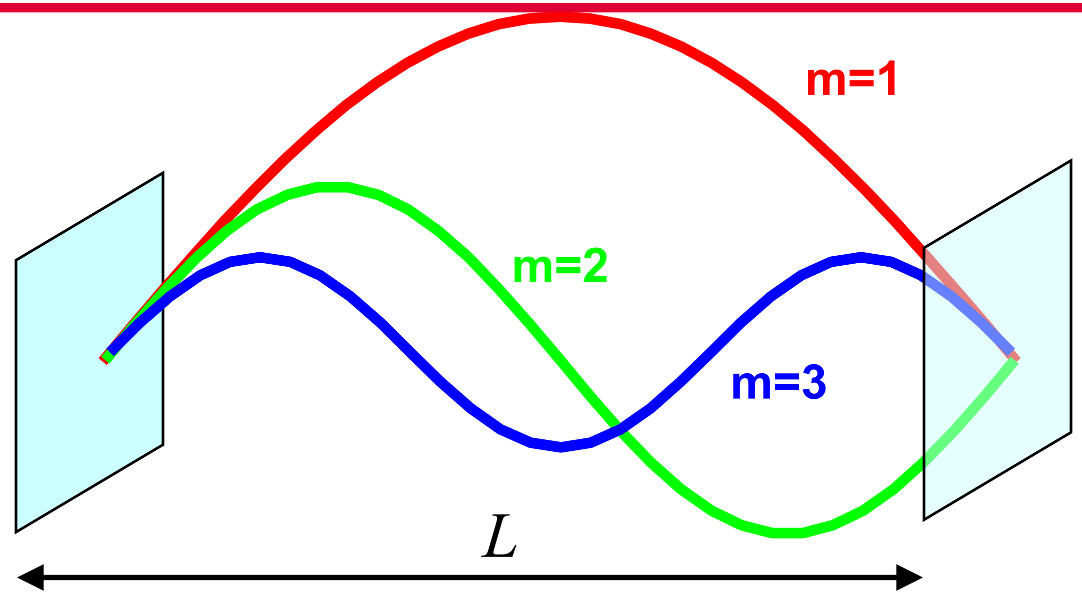
$$R = \left(\frac{n_{FP} - n_{air}}{n_{FP} + n_{air}} \right)^2$$

- For GaAs this reflection coefficient is

$$R = \left(\frac{3.6 - 1}{3.6 + 1} \right)^2 = 0.32$$



Fabry-Perot resonant modes



Refractive index in cavity

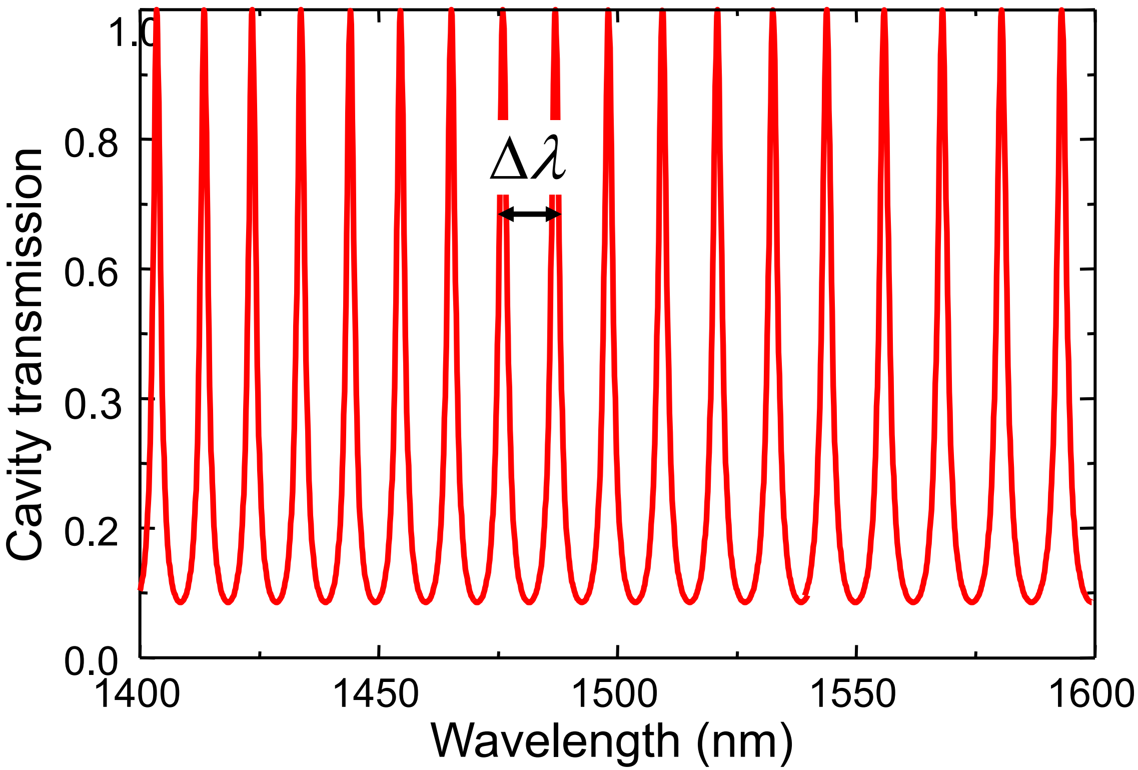
Cavity length

$$\lambda_m = \frac{2 n_r L}{m}$$

Longitudinal mode order

- Fabry-Pérot cavities sustains longitudinal modes. Each mode has a different wavelength
- In general, the laser cavity length L is equal to a few 100 µm → $m >> 1$

Longitudinal (axial) modes



The laser output consists of a large number of discrete frequency components.

To calculate mode spacing, first solve for *m*:

$$m = \frac{2n_r L}{\lambda_m}$$

Then differentiate and solve for $d\lambda$ (n depends on λ):

$$\Rightarrow \quad \frac{dm}{d\lambda} = -\frac{2Ln_r}{\lambda^2} + \frac{2L}{\lambda}\frac{dn_r}{d\lambda} \quad \Rightarrow$$

$$\Delta\lambda = \frac{\lambda^2}{2Ln_r}\left(1 - \frac{\lambda}{n_r}\frac{dn_r}{d\lambda}\right)^{-1}$$

Frequency separation of adjacent modes:

$$\Delta f = \frac{c}{2Ln_r}\left(1 + \frac{f}{n_r}\frac{dn_r}{df}\right)$$

Lasing condition

Loss γ **in the cavity**
Gain **g in active region**

Loss coefficient γ: takes into account all the losses (scattering, absorption, diffraction) except the transmission at the ends.

Gain inside the cavity after one round trip: $e^{2\Gamma g L - 2\gamma L}$

Mirror loss after one round trip: $R_1 R_2$

Optical intensity after one round trip: $I = I_0 R_1 R_2 e^{2(\Gamma g - \gamma)L}$

In order to be sustained, the light wave intensity should be the same after one round trip in the cavity

Lasing condition

Modal gain is a measure of the power transferred from the active region Into the propagating mode.

Modal gain

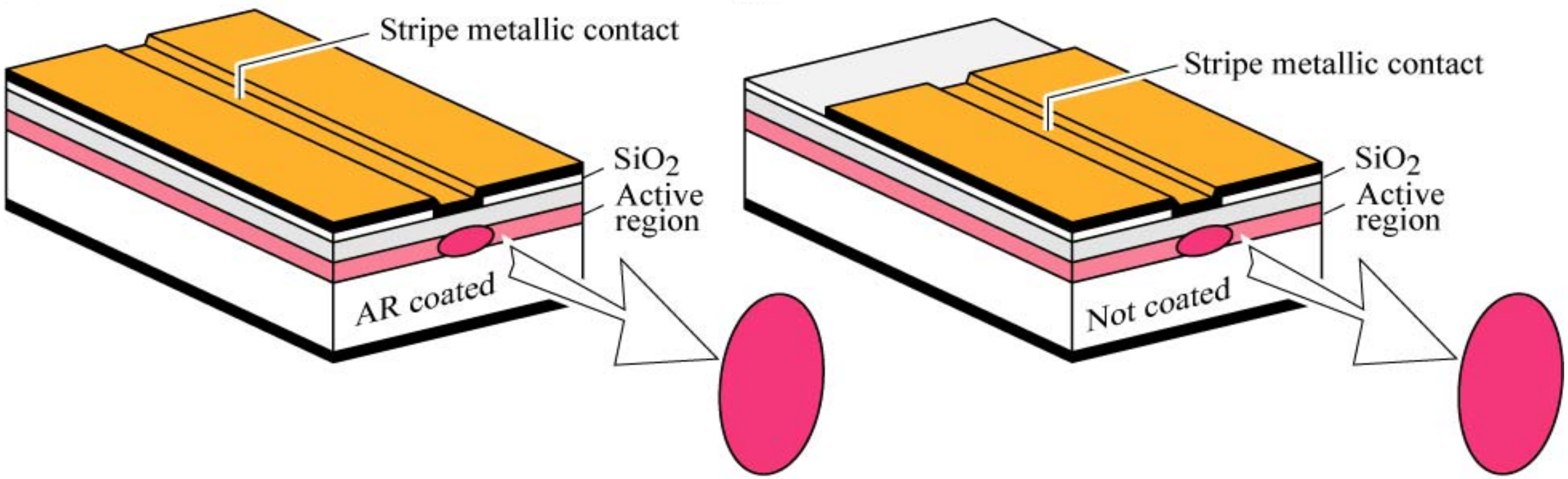
$$I = I_0 R_1 R_2 e^{2(\Gamma g - \gamma)L}$$

At threshold:

$$I = I_0 \Rightarrow \Gamma g_{th} = \gamma + \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)$$

Γ Is a measure of modal confinement (the fraction of optical intensity in the active region), and is a strong function of the active region thickness d. For example if d > 0.1 μm → Γ~1, if d ~ 5-10 nm → Γ < 0.05

Superluminescent LED

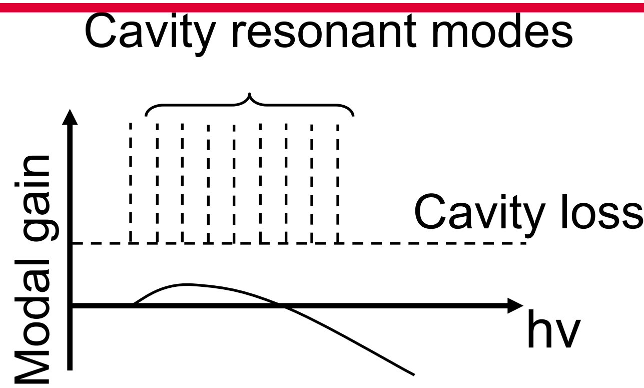


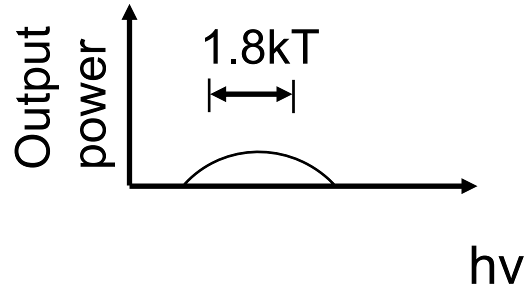
Superluminescence or **superradiance** occurs when the spontaneous emissions of **an edge emitting LED** is amplified by stimulated emission

A superluminescent LED has an output power density comparable to that of a laser diode.

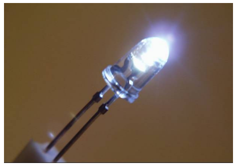
An anti-reflective (AR) coating or an absorbing section is used in order to avoid lasing

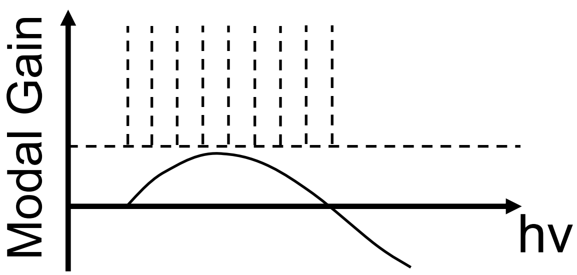
Gain and emission spectra

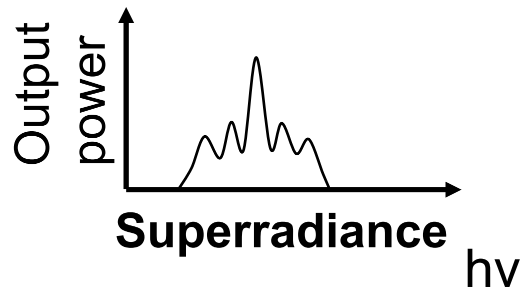




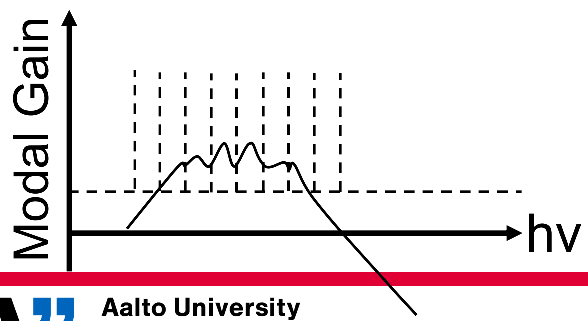
LED

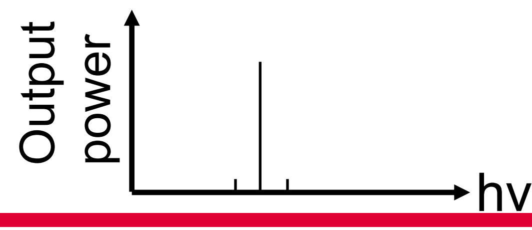




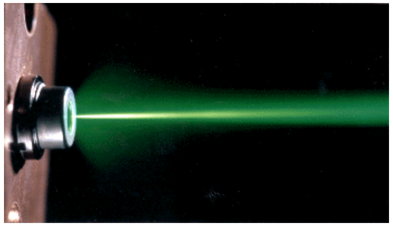


Superluminescent LED



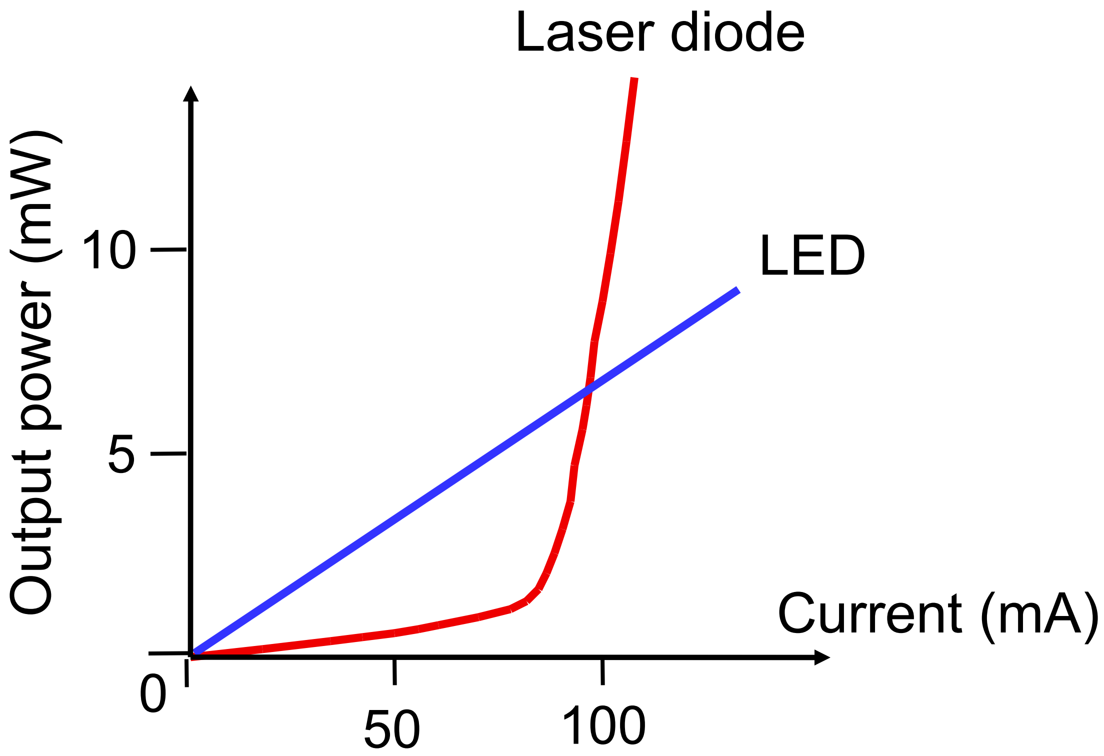


Laser diode

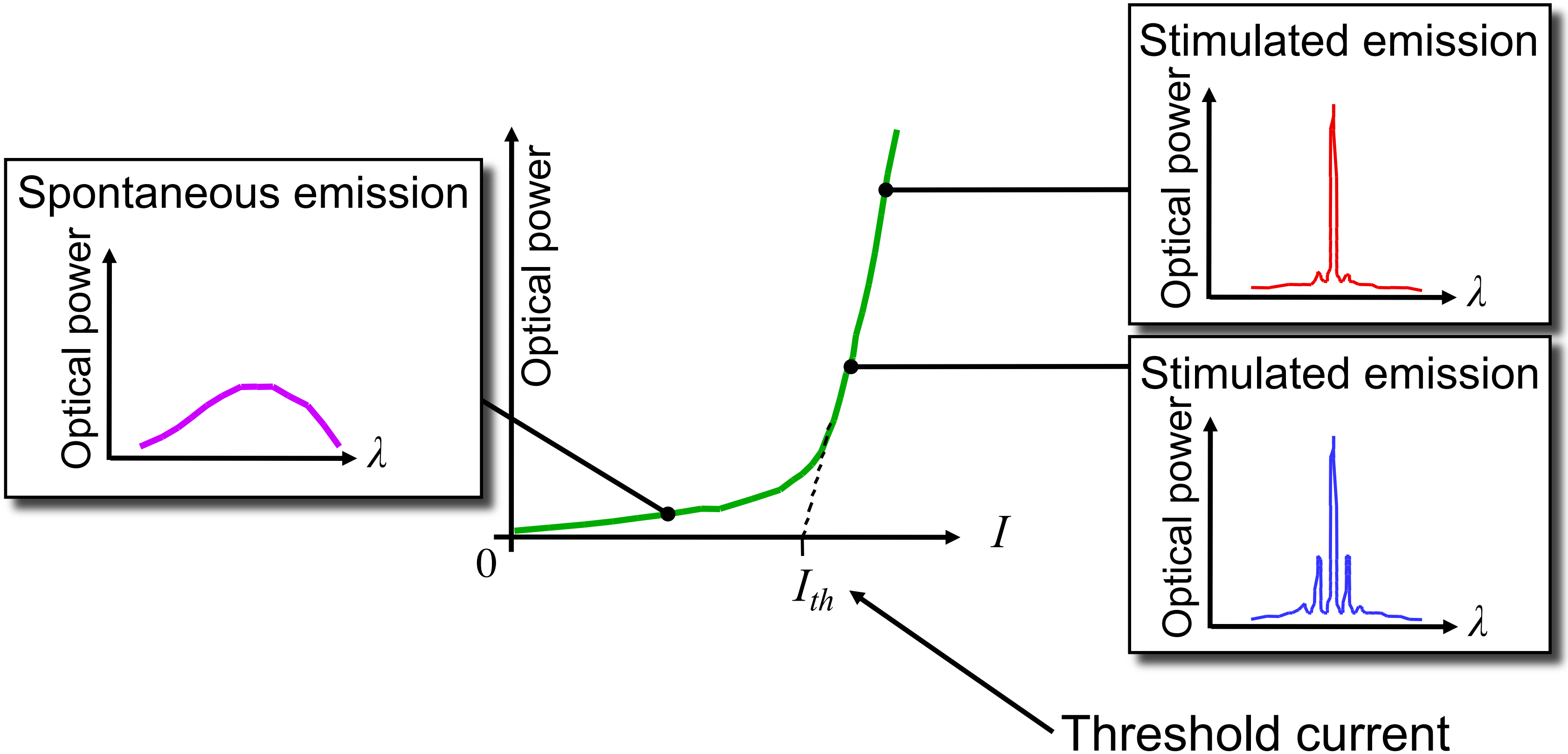


Optical power vs current

Comparison Laser-LED



Optical power vs current



Outline

1 **Introduction**

2 **The Fabry-Pérot laser**

3 **Transparency and threshold current**

4 **Heterostructure laser**

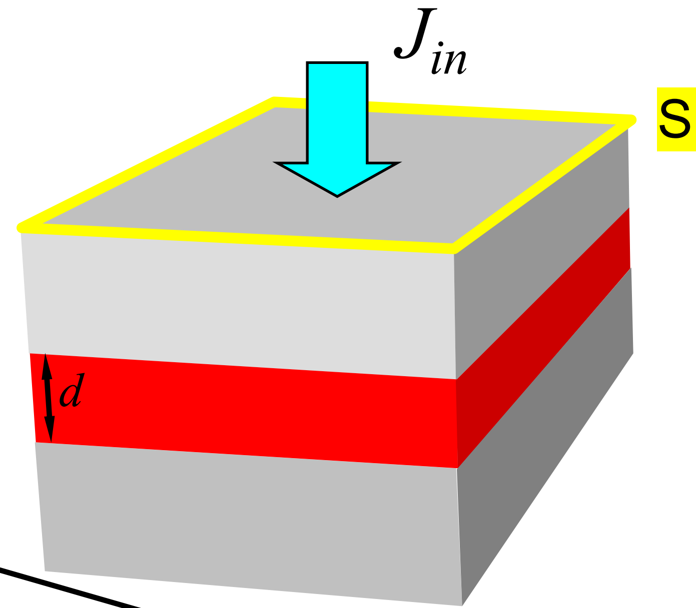
5 **Power output and linewidth**

P. Bhattacharya: chapters 6&7
J. Singh: chapter 10&11

Rate equation

We suppose that all injected carriers recombine in the active region (= **no current leaking**)

Number of electrons injected per second per unit volume of the active region (this number is removed in the steady state by recombination with a lifetime τ)

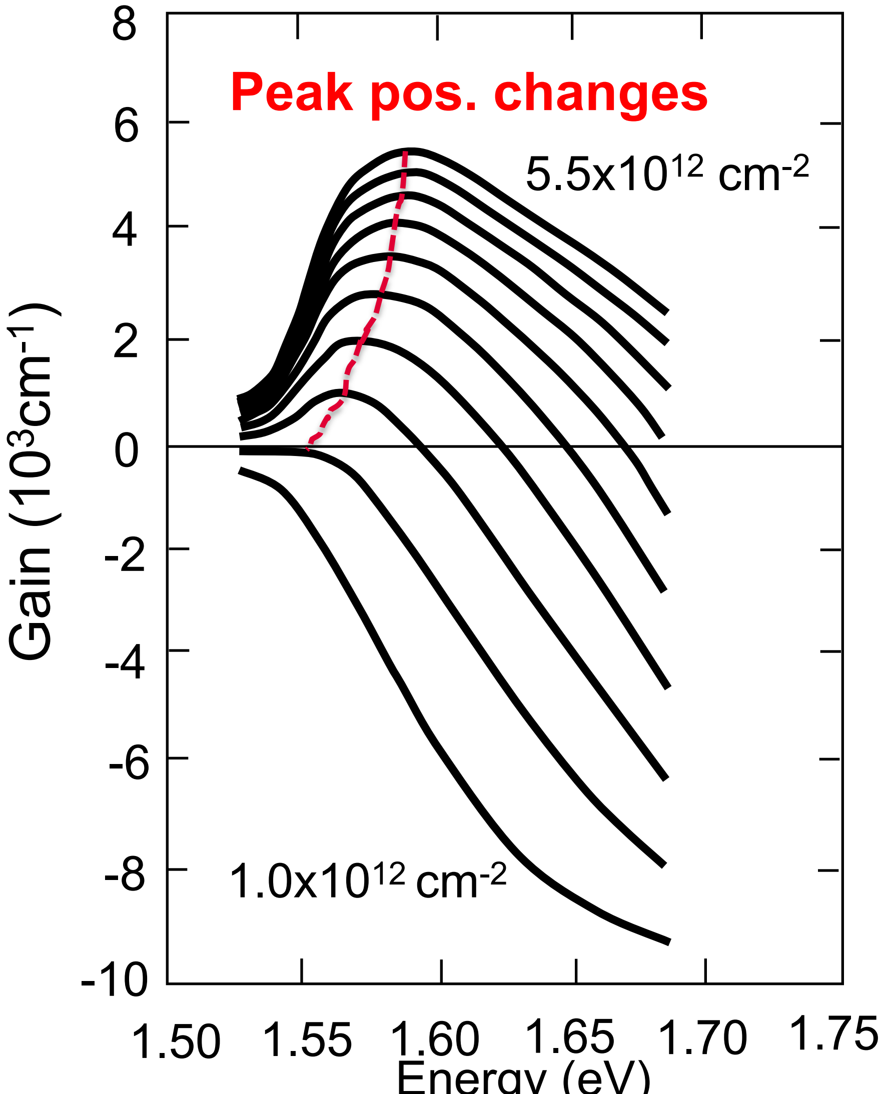


$$\frac{dN}{dt} = -\frac{N}{\tau} + \frac{1}{q}JS \quad \xrightarrow{\div Sd} \quad \frac{dn}{dt} = -\frac{n}{\tau} + \frac{1}{qd}J$$

Electron lifetime

In steady state: $$0 = \frac{n}{\tau} - \frac{1}{qd}J \quad \Rightarrow \quad J = qd\frac{n}{\tau}$$

Gain vs wavelength and electron density



Threshold current density (at n_{th} the peak gain matches the cavity loss):

$$J_{th} = qdR_{sp(n_{th})}$$

Assume that the peak modal gain is linear function of *n:*

$$\Gamma g\left(E_m\right) \cong \alpha\left(\frac{n}{n_{trans}} - 1\right)$$

α = absorption coefficient

n_{trans}=carrier density that makes the medium transparent (emission balances absorption and $g(E_m) = 0$)

Transparency current

- We suppose that the maximal gain $g(n,\lambda_0)$ depends **linearly** on the carrier density n.

$$\Gamma g(E_m) = \alpha\left(\frac{n}{n_{trans}} - 1\right) = \alpha\left(\frac{J}{J_{trans}} - 1\right)$$

Absorption in the active region when n=0 (no carrier injection) [α]

Electron density at transparency [n_{trans}]

- At lasing threshold:

$$J_{trans} = qd\frac{n_{trans}}{\tau}$$

$$\Gamma g(E_m) = \Gamma g_{th} \Rightarrow J_{th} = \frac{\Gamma g_{th} + \alpha}{\alpha} J_{trans}$$

$$\Rightarrow \quad J_{th} = J_{trans} + \frac{J_{trans}}{\Gamma\alpha}\left(\gamma + \frac{1}{2L}\ln\frac{1}{R_1 R_2}\right)$$

Threshold current density

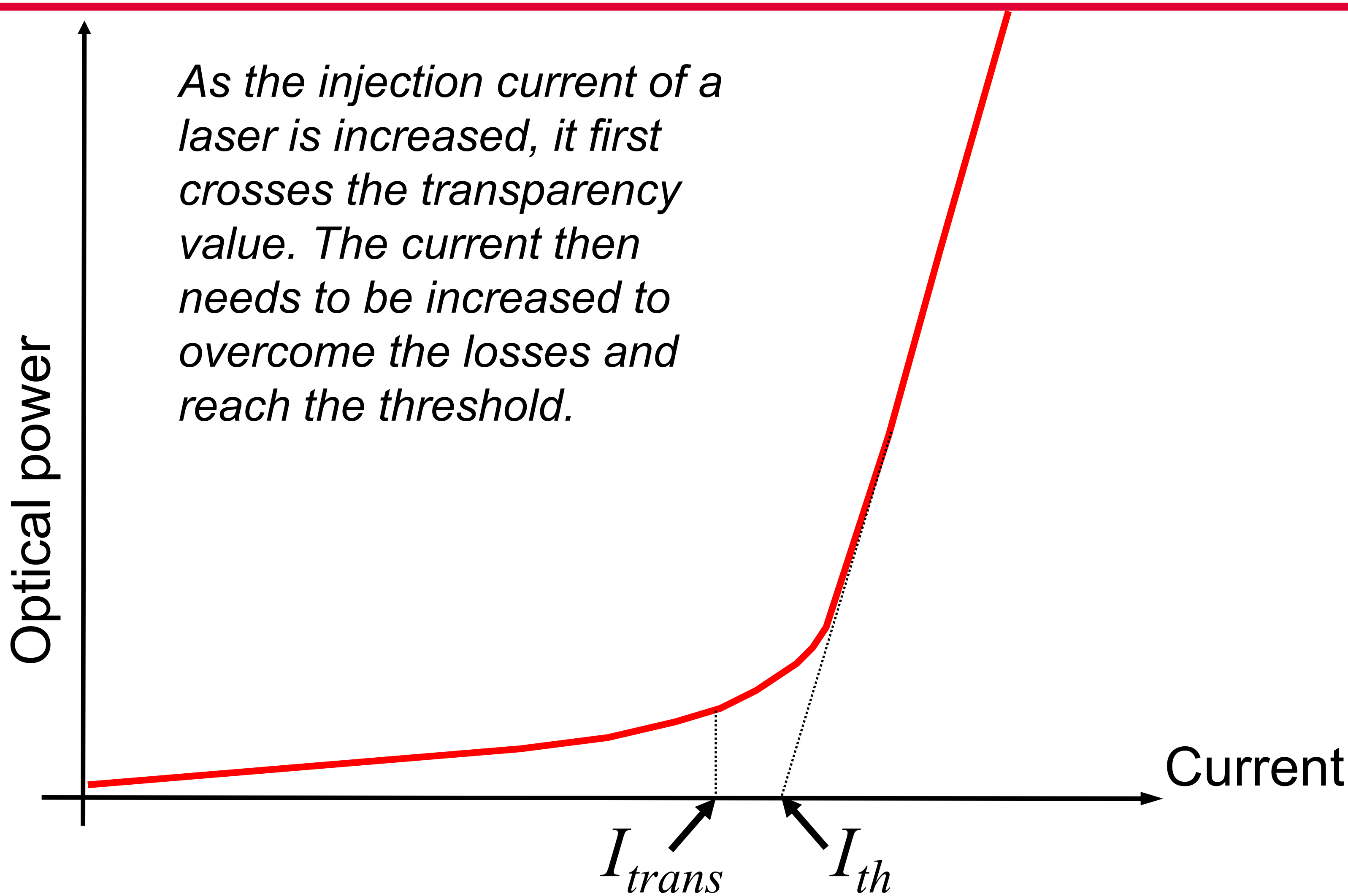
- We introduce the differential gain $\frac{\partial g}{\partial n} = \frac{\alpha}{n_{trans}}$

- Let us insert this expression in the expression for the threshold current density:

$$J_{th} = J_{trans} + \frac{qd}{\Gamma \tau \frac{\partial g}{\partial n}} \left(\gamma + \frac{1}{2L} \ln \frac{1}{R_1 R_2} \right)$$

Optical power vs. current

As the injection current of a laser is increased, it first crosses the transparency value. The current then needs to be increased to overcome the losses and reach the threshold.



Threshold current density

Threshold current density can be reduced by:

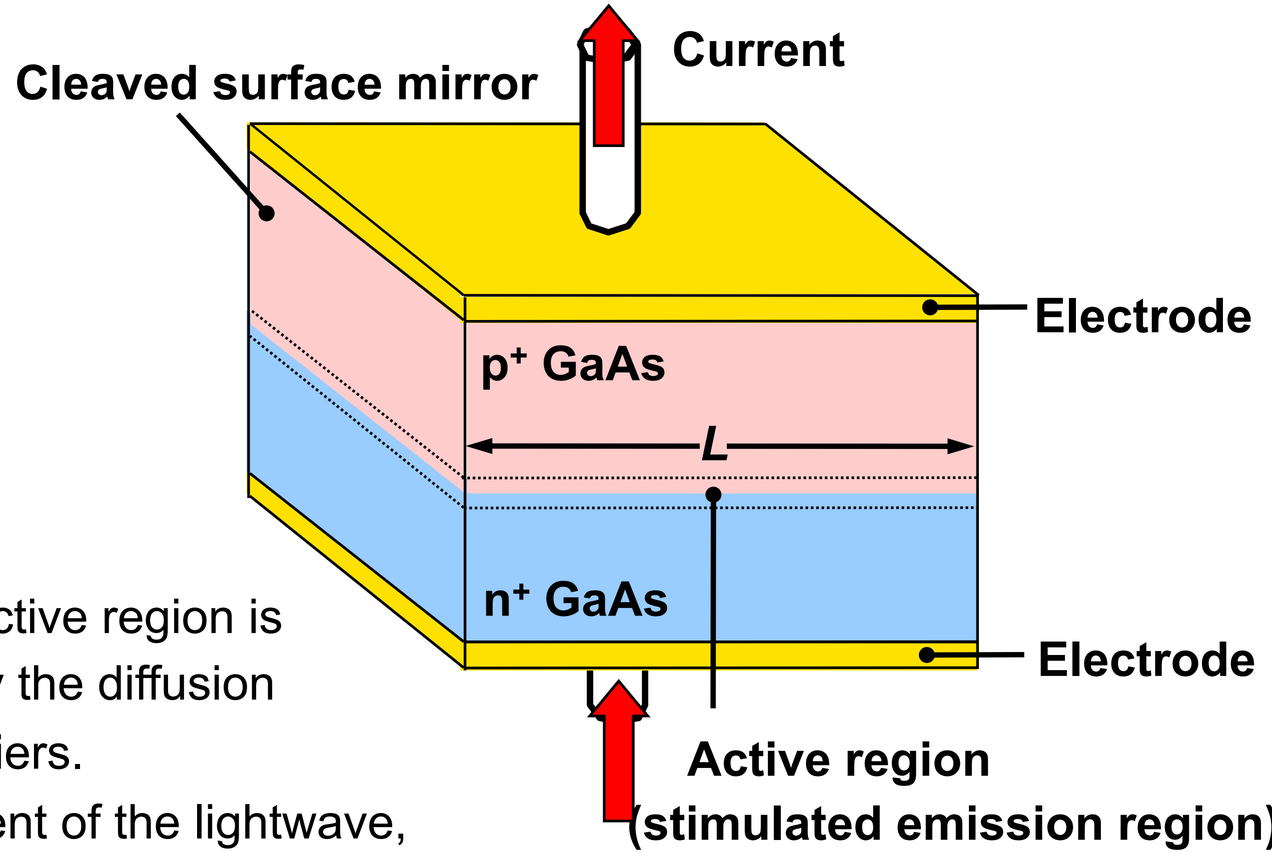
- reducing *d*
- increasing η_i
- increasing the differential gain
- reducing the cavity and mirror losses

With the other parameters remaining constant and $\Gamma \cong 1$, J_{th} decreases with decrease of *d*. However, with further reduction of *d*, Γ becomes less than unity as the optical mode extends beyond the active region. As a result, J_{th} will increase again.

Outline

P. Bhattacharya: chapters 6&7
J. Singh: chapter 10&11

Homojunction laser

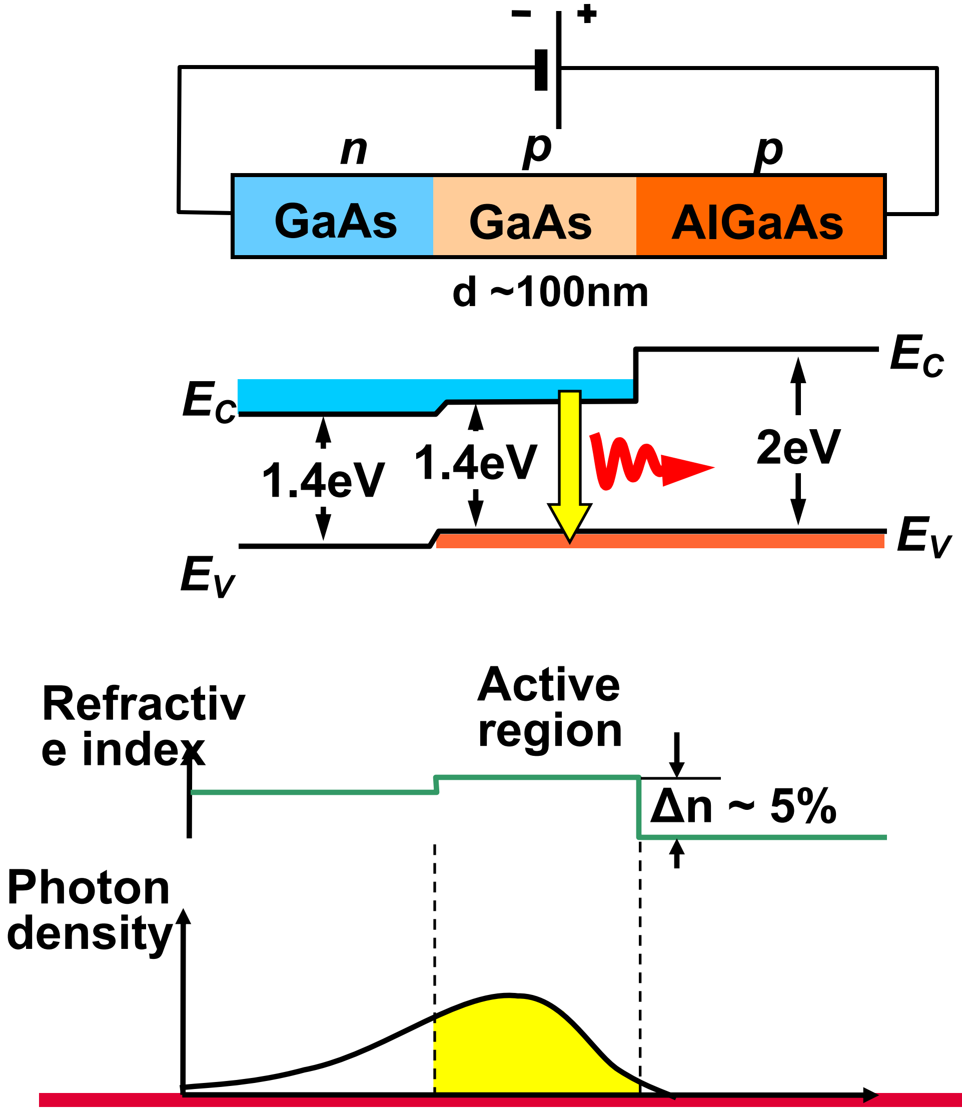


- The thickness of the active region is large since it is defined by the diffusion length of the minority carriers.
- No effective confinement of the lightwave, high cavity losses

→ **Large threshold current**

Therefore works only at cryogenic temperature!

Single heterostructure laser



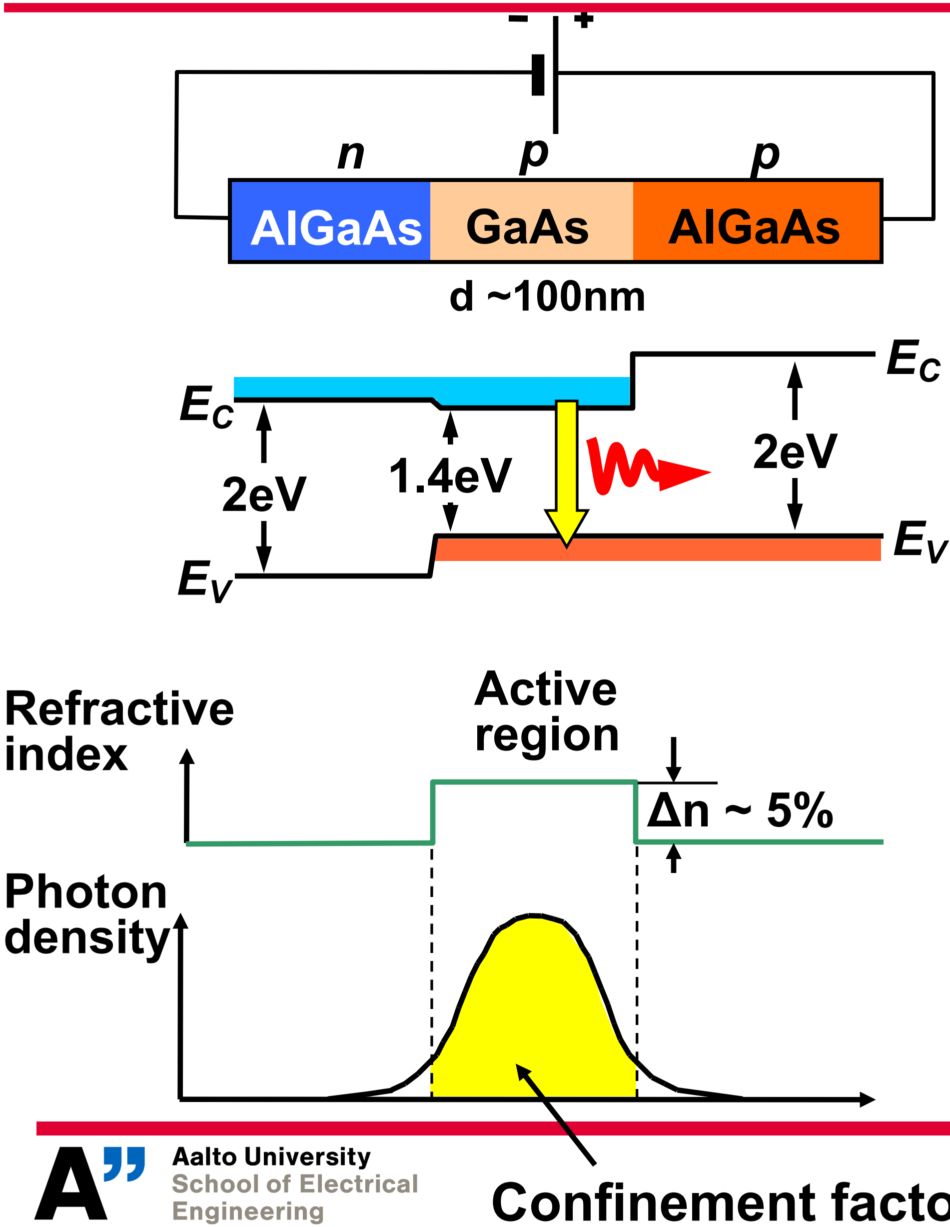
Light amplification takes place in the active region, the p-doped GaAs.

Higher bandgap p-AlGaAs layer provides a potential barrier for electron diffusion → **carrier confinement**

The refractive index of AlGaAs is smaller than that of GaAs → **optical mode confinement**

The single heterostructure allows a better light confinement than the homostructure.

Double heterostructure



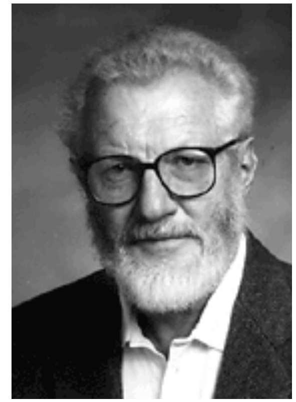
A double heterostructure diode has two junctions between two different bandgap semiconductors like GaAs and AlGaAs. Light amplification takes place in the active region, the p-doped GaAs.

Higher bandgap materials have a lower refractive index. Therefore AlGaAs layers **provide optical confinement on both sides of the active region**

The double heterostructure allows to achieve both carrier and light confinement !

Double heterojunction

Zhores I. Alferov



Herbert Kroemer

…received the Nobel Price in Physics in 2000 for developing semiconductor heterostructures used in high-speed- and opto-electronics

In a heterojunction laser Γ remains nearly equal to unity due to confinement of the mode within the well-defined active region.

→ Much lower threshold current densities are therefore achieved.

Outline

P. Bhattacharya: chapters 6&7
J. Singh: chapter 10&11

Power output

Optical power output into the modal volume due to current J

$$P = A(J - J_{th})\frac{\eta_i h\nu}{q}$$

Laser output power:

$$P_0 = A(J - J_{th})\frac{\eta_i h\nu}{q}\boxed{\frac{1/2l\ln(1/R_1R_2)}{\gamma + 1/2l\ln(1/R_1R_2)}}$$

- A is the junction area
- η_i is internal quantum efficiency

Fraction of the power coupled out through facets, the rest is used to overcome losses γ within the cavity

Differential quantum efficiency
(the increase in light output due to an increase in drive current)

$$\eta_d = \frac{d(P_0/h\nu)}{d(A/q|J - J_{th}|)}$$

Power output

$$\eta_d = \eta_i \frac{\ln(1/R)}{\gamma l + \ln(1/R)}$$

Differential quantum efficiency

η_i and γ can be estimated from a measured dependence of η_d on cavity length l

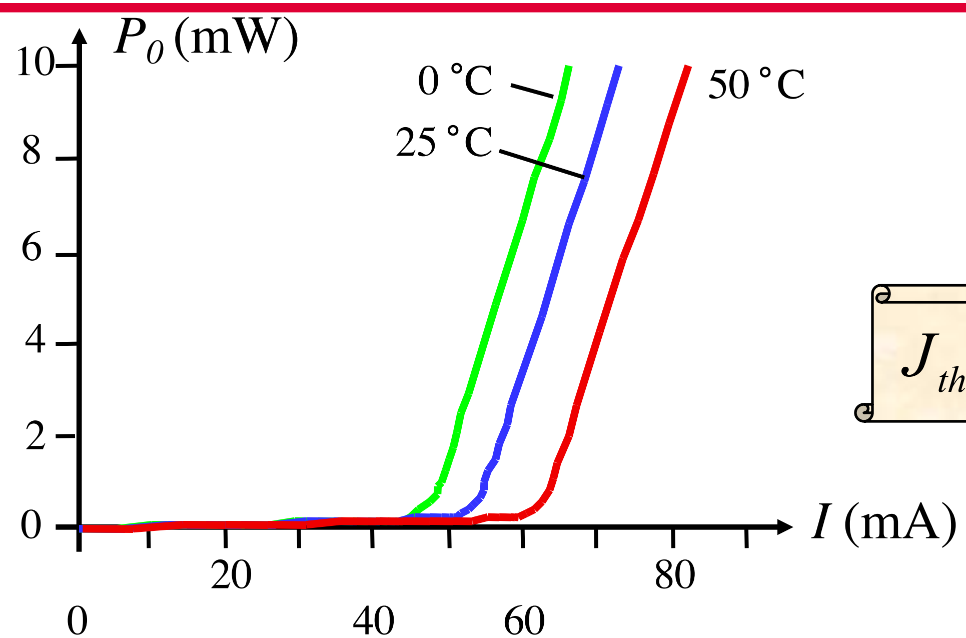
Power conversion efficiency:

$$\eta_P = \frac{P_0}{V_f A J}$$

insert P_o

$$\eta_P = \frac{\eta_i h\nu}{q V_f}\left(\frac{J - J_{th}}{J}\right)\frac{\ln(1/R)}{\gamma l + \ln(1/R)}$$

Temperature dependence



$$J_{th}(T) = J_{th}(0)\exp\left(T / T_0\right)$$

- Increase of the threshold current with temperature is due to:
  - Energy spreading of the carriers
  - Increased carrier leakage from the active region
  - Increased Auger recombination rate

• **Characteristic temperature** T_0 is in general higher in wider bandgap materials:

AlGaAs/GaAs: 100-200 K InGaAsP: 40-80 K

Linewidth of the modes

• Emission linewidth is determined by optical process occurring in the active region

• Spontaneous emission leads to amplitude and phase fluctuations of the light waves and thereby determines the spectral width of the emission line

• The linewidth of a single longitudinal mode is determined by the phase fluctuations of the optical field in the laser cavity

$$\Delta f \propto \Delta f_0 + f\left(1+\beta^2\right)$$

Linewidth enhancement factor: $\beta = -\frac{4\pi}{\lambda}\frac{\Delta n_r}{\Delta g}$

Cavity Q-factor is a measure of the mirror losses: $Q = \frac{\omega_0}{\Delta\omega}$

Line-broadening mechanisms

Homogeneous broadening: all parts of the gain medium are affected uniformly

- Occurs mainly due to phonon interactions

Inhomogeneous broadening: only selected parts are affected

- is due to local variations of the electronic properties across the sample (localized strain, impurity density variations, alloy clustering, interface roughness etc.)

Line-broadening function: $$\int_{-\infty}^{\infty} S(\nu)\, d\nu = 1$$

The total gain: $$g(E) = \int g(E')\, S(E - E')\, dE'$$

$$S(\nu_0) \cong \frac{\nu_0}{\Delta\nu}$$

← Frequency corresponding to the peak of the spontaneous emission spectrum