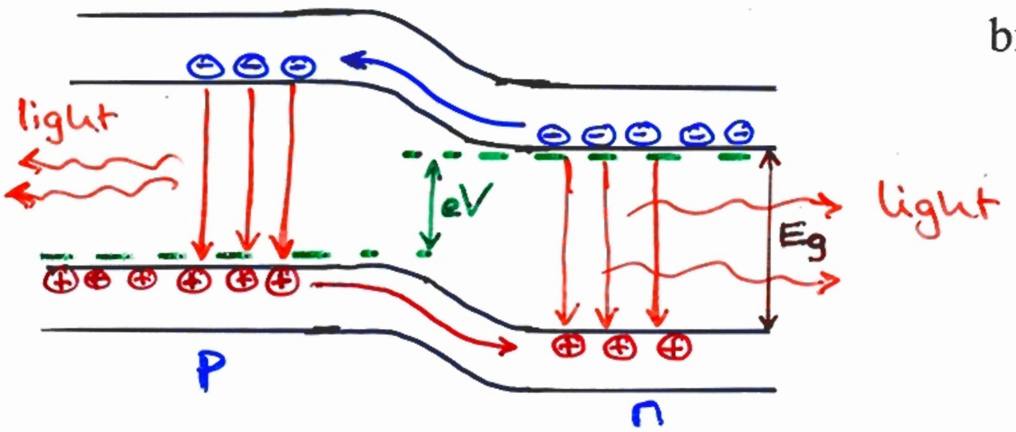
Semiconductor Opto-Electronic Devices

(light emitting diodes LEDs and lasers)

LEDs

Forward bias

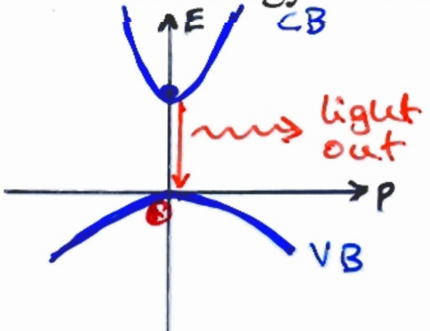
V = forward bias voltage



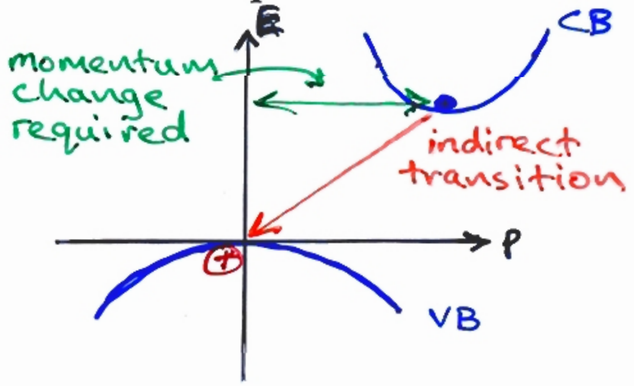
$$\text{Energy of photons } = E_g = \frac{hc}{\lambda}$$

eg. GaAs $E_g = 1.44\text{eV} \Rightarrow \lambda = 860\text{nm}$

Electrons and holes injected across this junction under forward bias recombine with majority carriers and produce photons of energy = bandgap



Direct band-structure
- efficient recombination.
e.g. GaAs, InP, InGaAs

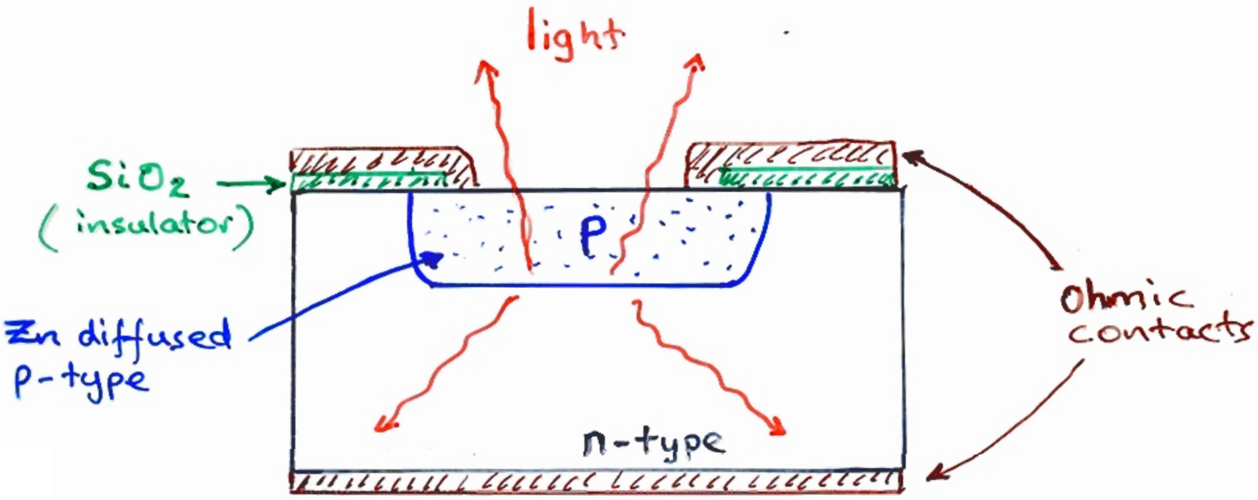


Indirect band structure
- poor recombination - need momentum change - phonon, interaction with lattice
e.g. Si, Ge

Emitted wavelength determined by choice of material.

InAs	3800nm (mid I.R.)	environmental monitoring
InGaAs	1300→1550nm (near I.R.)	optical fibre communications (laser) CD players (laser)
AlGaAs	800nm – 780nm	
GaP	690nm (red)	
GaInP	550 – 570nm (green/yellow)	
GaN	340 – 590 (blue UV)	next generation DVD players (laser)

Typical LED structure



Internal (quantum) efficiency $= \frac{\text{number of photons created}}{\text{number of injected e-h pairs}}$

(Some electron-hole pairs lost through non-radiative re-combination)

Crystal quality improves efficiency (50% efficiency required for are lighting applications)

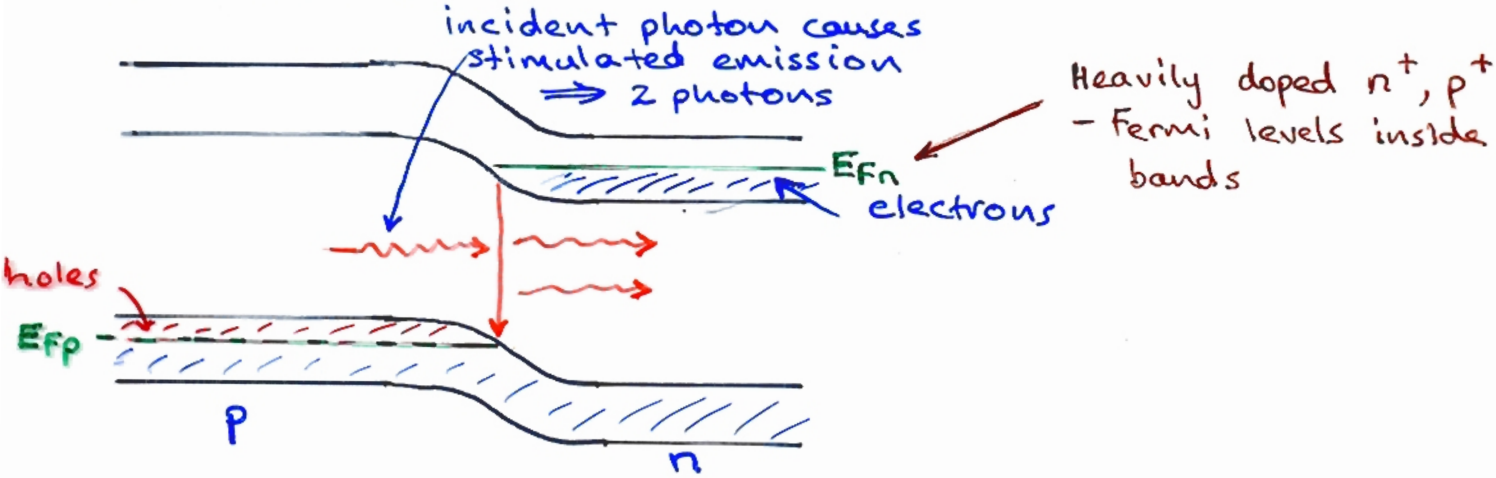
Also, in terms of power

$$\text{efficiency} = \frac{\phi}{IV}$$

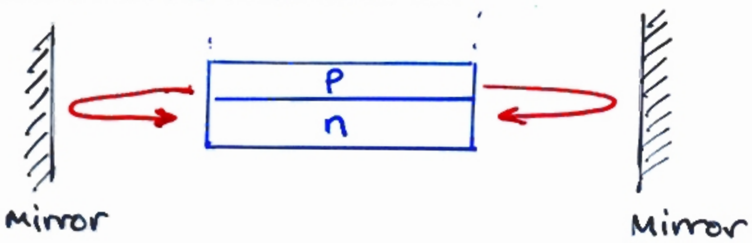
ϕ is not easy to measure hence using external efficiency which takes account of photons lost by absorption and reflection.

Semiconductor Lasers

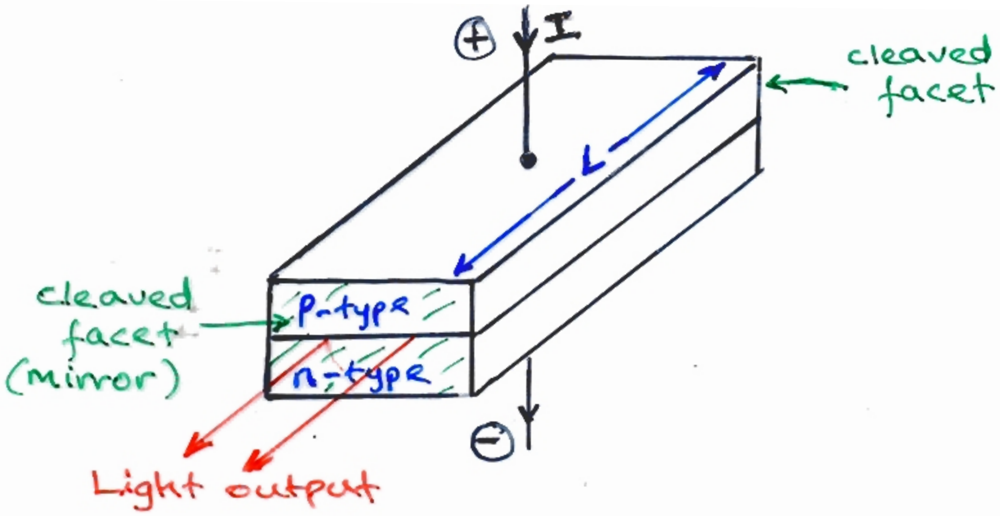
Similar to LEDs but photons are 'fed-back' to cause stimulated emission.



Feedback achieved with mirrors

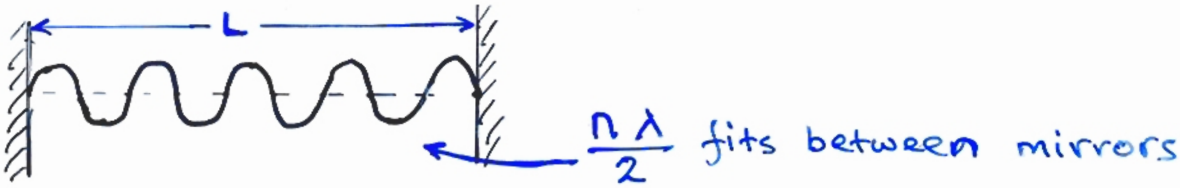


In practice smooth vertical crystal edges act as mirror with ~ 30% reflectivity Anti Reflection (AR) coatings can increase this to > 99%

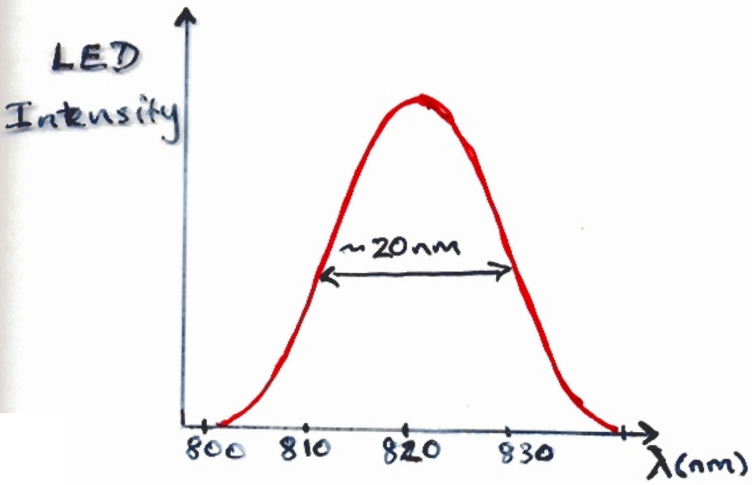


Get constructive interference in optical cavity when $\frac{n\lambda}{2} = L$,

therefore $\lambda = \frac{2L}{n}$ where n = integer

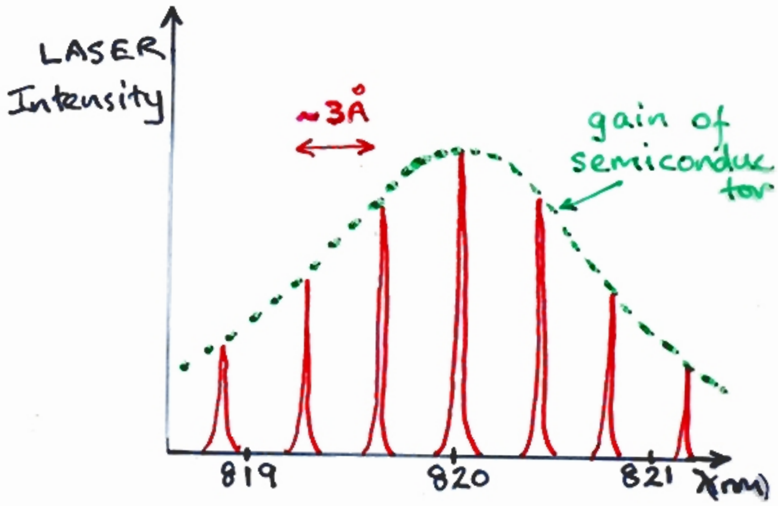


Spectral Output



Broad linewidth centered ~ on material band-gap.

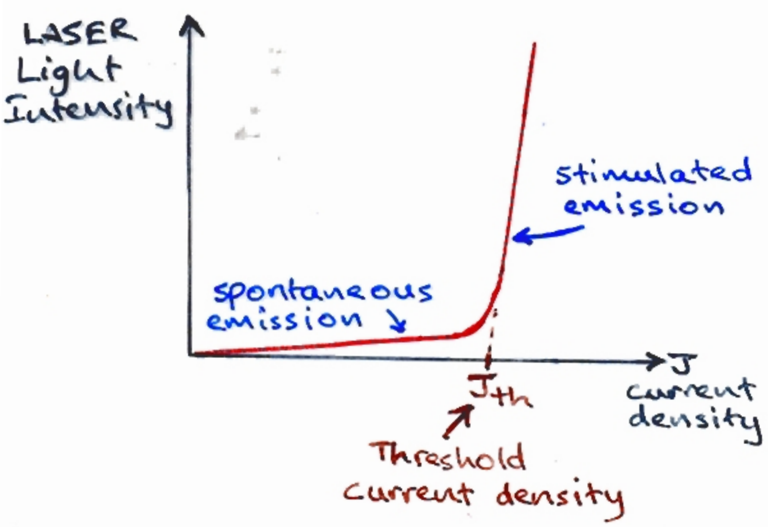
- Photons have a spread in energy
- Photons have no phase relationship with each other – i.e. random
- Spontaneous emission



Linewidth of each mode is very narrow compared to LED. ~ 6 longitudinal modes covering 2nm.

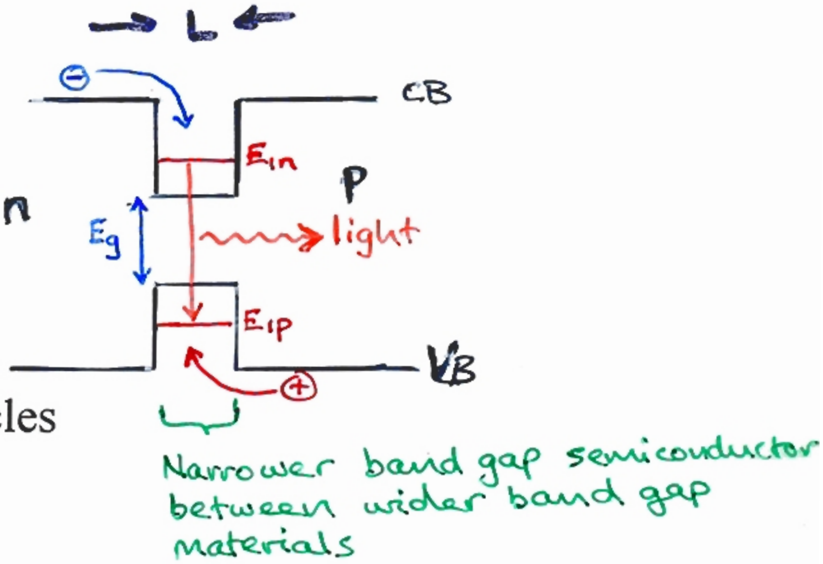
- Photons have almost identical energies
- Photons have the same phase relationship with each other – coherent
- Stimulated emission

L-I characteristic



At J_{th}, device gain = loss

<u>Quantum Well Laser</u>



Fully forward biased

Electrons and holes form quantum confined states

From section on Bound particles

$$E_{1n} = \frac{n^2h^2}{8mL^2}$$

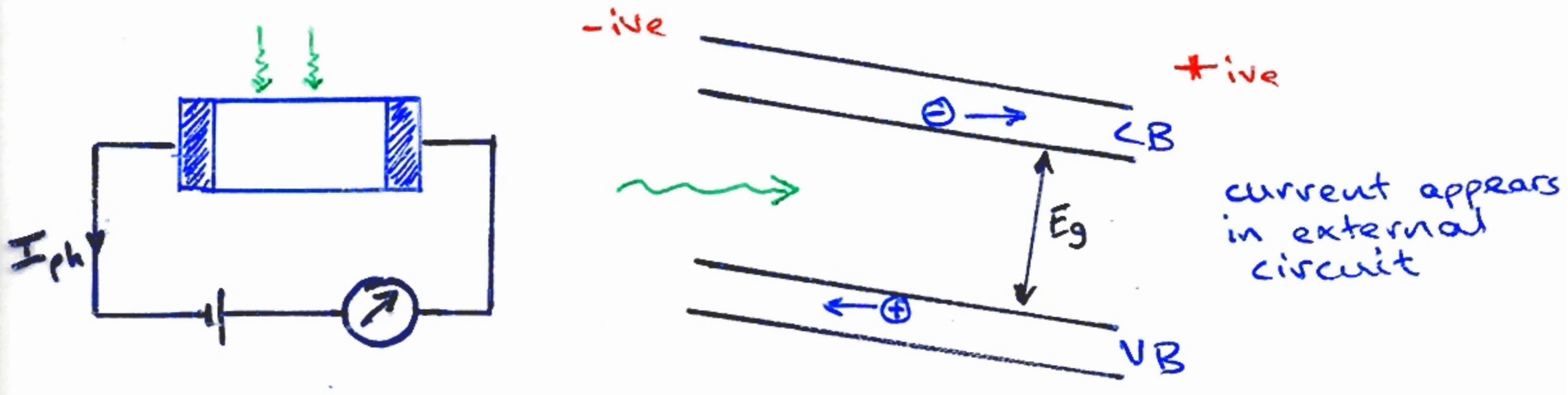
m different for e, h

Hence wavelength determined by <u>$E_g + E_{1n} + E_{1p}$</u>
Also quantum well lasers are much more efficient than 3-dimensional structures.

Detectors

Work by absorbing photons which produce e-h pairs.

a) **Photoconductors** – conductivity increases (current) as light intensity increases.



Photon energy $\geq$ Eg for this to work.

Also semiconductor needs to be high resistivity in the dark.

No light $\sigma \approx 0$

Apply light $\sigma = e(n_e\mu_e + p_h\mu_h)$

but $n_e = p_h$ therefore, $\sigma = en(\mu_e + \mu_h)$

Assume light of frequency ω (energy $\hbar\omega$)

Input optical power P (J/s)

Number of e-h pairs generated / sec = $\left(P/_{\hbar\omega}\right) \text{x } \eta$,

where η = efficiency

η = (no. of e-h pairs)/(no. of photons)

However, some of these e–h pairs will recombine before they reach the contacts.

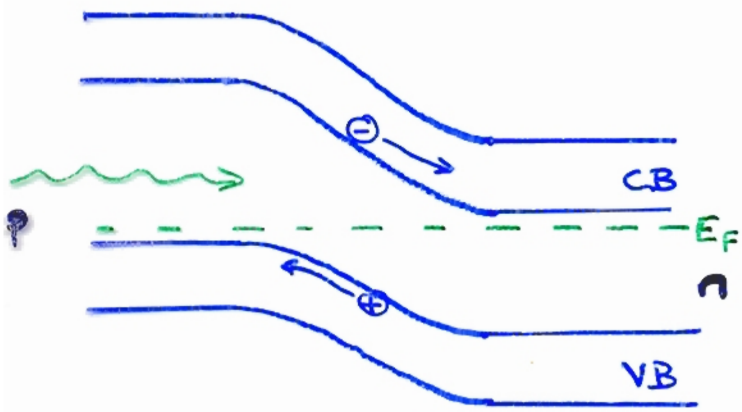
Hence, equilibrium number of e-h pairs.

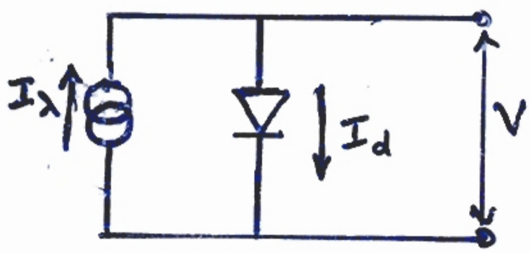
$$= \frac{\eta P \tau}{\hbar\omega} \quad \text{where } \tau = \text{life time of e-h pairs}$$

Since $I_{ph} \propto \sigma$, light intensity $\propto$ current
(watts/unit area)

b) Photodiode

Equivalent Cct.





Built-in field (can also be reverse biased) causes e-h pairs to be separated to produce current or voltage (open circuit).

From equivalent circuit,

diode current $I_d = I_o \left[\exp\left(\frac{eV}{kT}\right) - 1\right]$

For open circuit $I_d = I_\lambda$ (input current due to arriving photons)

$$= \frac{\eta e P}{\hbar\omega}, \text{ (from above)}$$

= charge arriving/sec

$$I_\lambda = \frac{\eta e P}{\hbar\omega} = I_o\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

$$\Rightarrow V = \frac{kT}{e}\ln\left[\frac{\eta e P}{\hbar\omega I_o}\right] \qquad \text{photovoltaic mode}$$

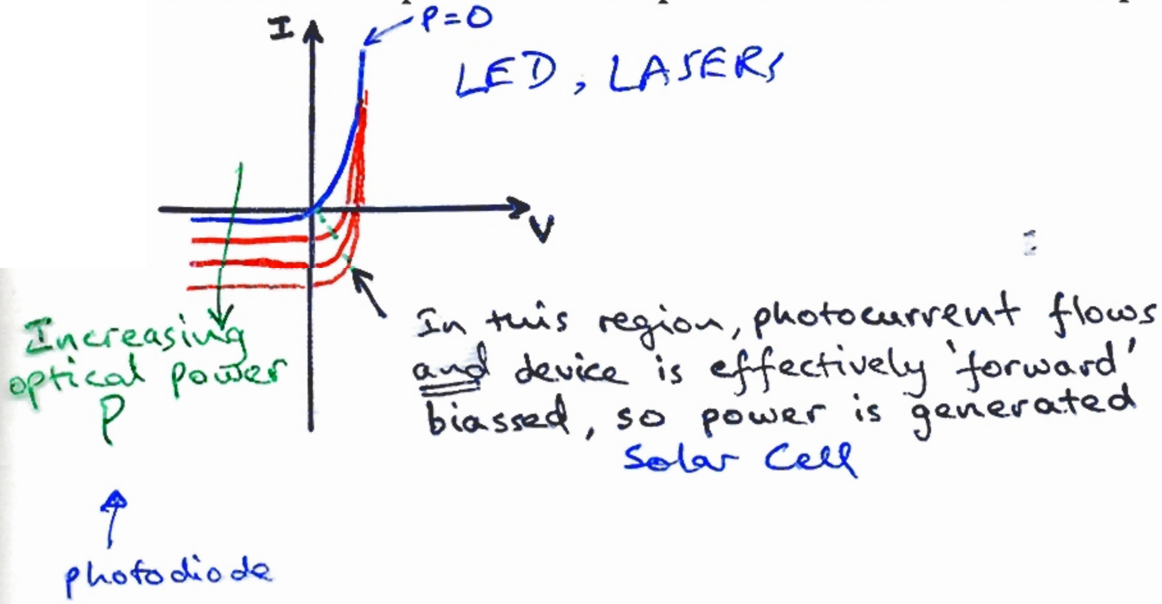
(Photoconductive mode -connected to external voltage source)

$$I_{ext} = I_d - I_\lambda = I_o\left[\exp\left(\frac{eV}{kT}\right) - 1\right] - \frac{\eta e P}{\hbar\omega}$$

First term small if reverse biased.

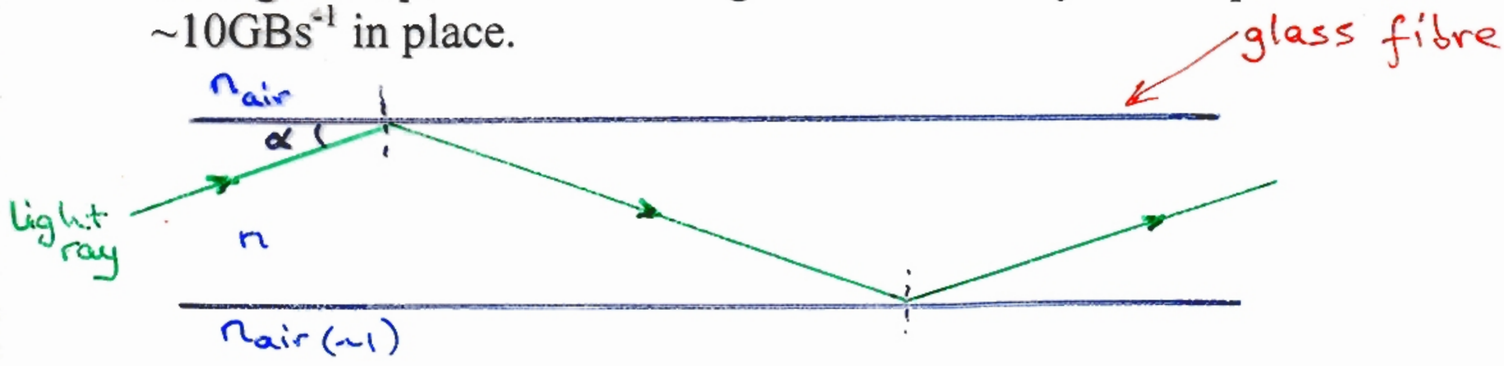
Hence $\quad I_{ext} = -\dfrac{\eta e P}{\hbar\omega}$

Solar cell – photodiode optimised for maximum power



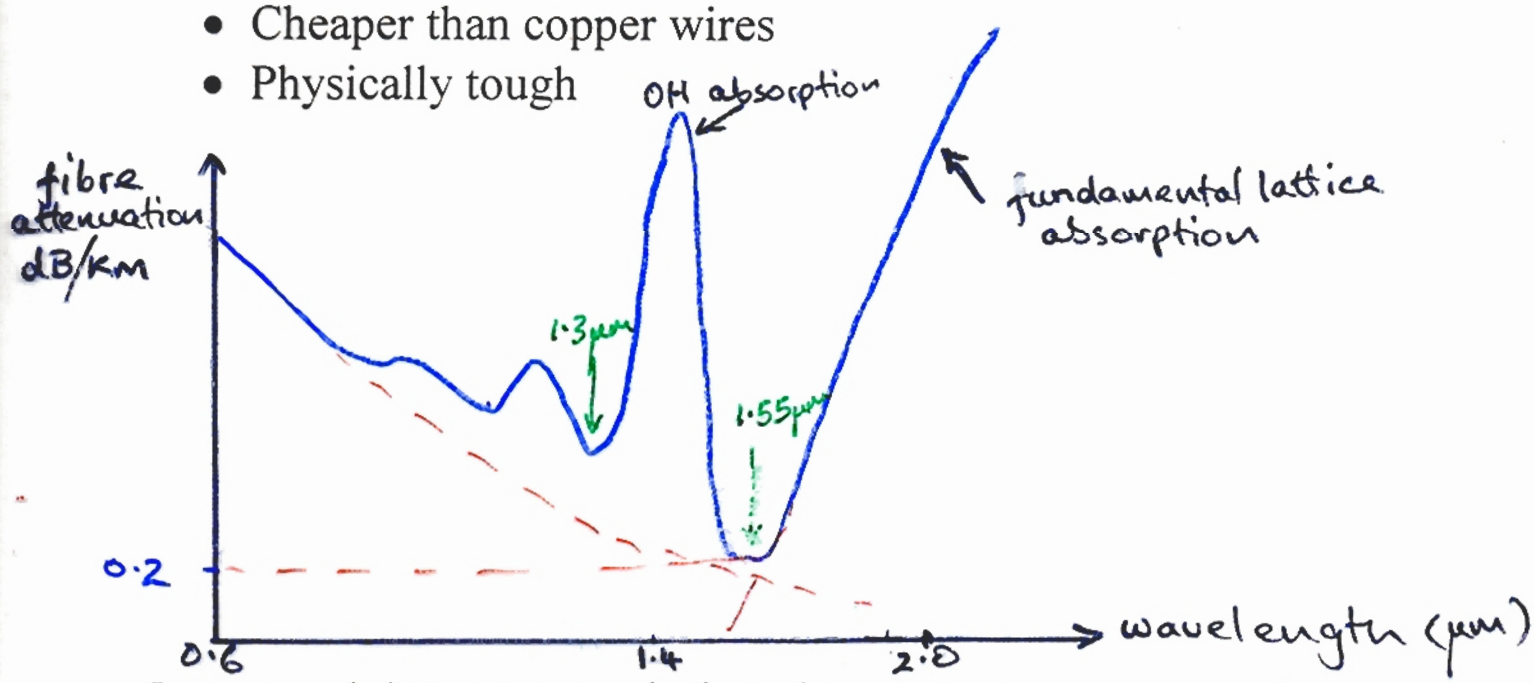
Fibre Optic Communications

Lasers and LEDs can be modulated digitally and passed through an optical fibre waveguide – current systems up to ~10GBs^{-1} in place.



If α is < a critical angle dependent on n and n_{air} (~1) light is totally reflected inside fibre and signal is guided through fibre.

- High bandwidth
- Low attenuation
- Light weight, small size
- No EM interference
- Immune to tapping or jamming – 'secure'
- No cross talk
- Cheaper than copper wires
- Physically tough



Lasers and detectors are designed to operate at 1.3µm and 1.55µm low-loss-windows.