ECEN 462: Fiber Optic Communications

Sam Carey, from Dr. Eknoyan

March 24, 2015

1 LaserDiode

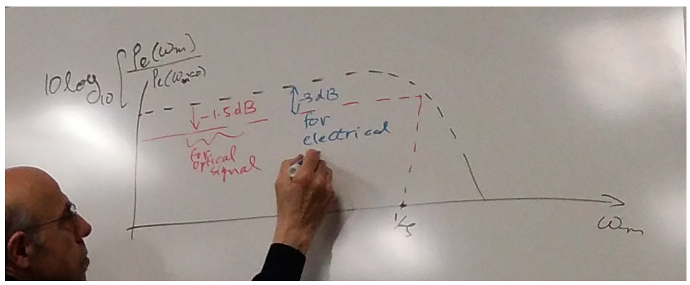

Figure 1: Images/image0.jpg

1.1 Continued: 3/10

For stimulated emission to dominate:
i) Spontaneous Emission: Material should provide gain
ii) Absorption: need POPULATION INERSION
iii) In semiconductor diode lasers, these conditions can be satisfied by:
a) Using cleaved end facets (mirrors) to reflect light back and forth & induce gain. Since light is an EM wave, this also establishes resonant cavity behavior.
b) Using high current injection across heavily doped pn junction produced in direct bandage S/C material.

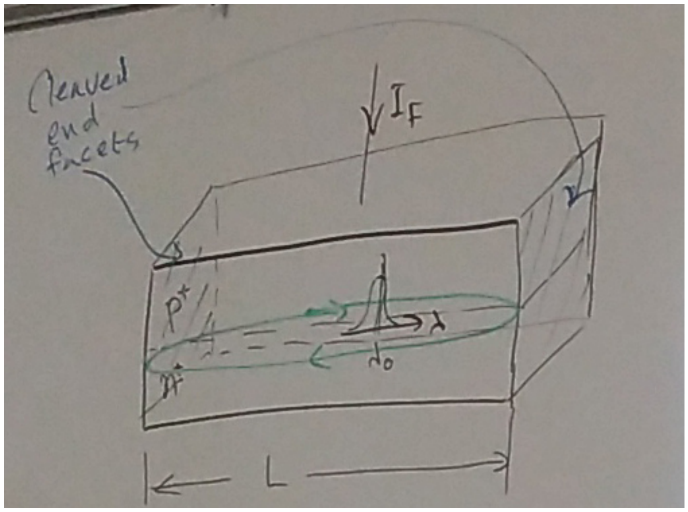

Figure 2: Images/image1.jpg

As light reflects back and forth, it suffers losses due to 1) absorption in material and 2) reflection at end facets. To overcome losses, increase drive current. When total losses in one round-trip equals gain, then threshold is established. If I_{th} is increased above I_{th}, then lasing occurs.

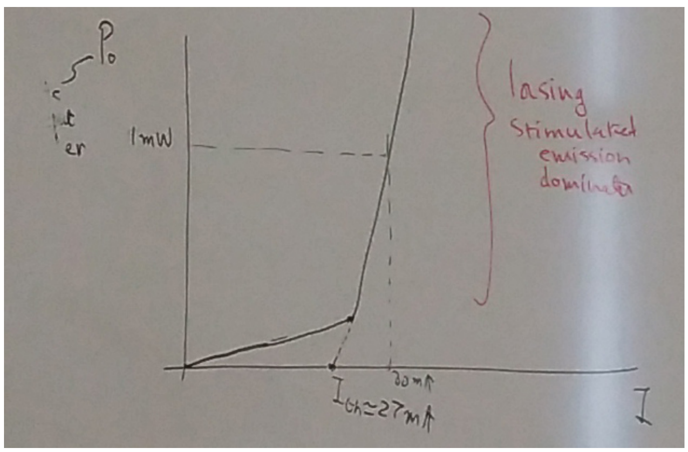

Figure 3: Images/image2.jpg

For light bouncing back and forth to add up constructively, the accumulated phase for one round trip must be $m(2\pi)$, where $m = 1, 2, 3, ...$ The phase accumulated over a distance of travel z:

$$\theta = \frac{2\pi}{\lambda_0 n z}$$

where n is the refractive index of material. For a round trip:

$$z = 2L \rightarrow \frac{2\pi}{\lambda_0 n 2L} = m(2\pi)$$

Since L is fixed, $\lambda \rightarrow \lambda m$:

$$\frac{n2L}{\lambda m} = m$$

$$\lambda = \frac{c}{f}$$

or

$$\frac{n2L}{c/f_m} = m \rightarrow f_m = \frac{mc}{2Ln}$$

Spacing int frequency between two consecutive resonant frequencies:

$$\Delta f = f_{m+1} - f_m = \frac{[(m+1) - m]c}{2Ln} = \frac{c}{cLn}$$

from

$$f = \frac{c}{\lambda}, \frac{\Delta f}{f_0} = \frac{\Delta\lambda}{\lambda_0}$$

or

$$\Delta\lambda = \frac{\lambda_0 \Delta f}{f_0} = \frac{\lambda_0 \Delta f}{c/\lambda_0} = \frac{\lambda_0^2}{c}\frac{c}{2Ln} = \frac{\lambda_0^2}{2Ln}$$

$$(\Delta\lambda)_{lm}(\text{longitudinal modes}) = \frac{\lambda_0^2}{2Ln}$$

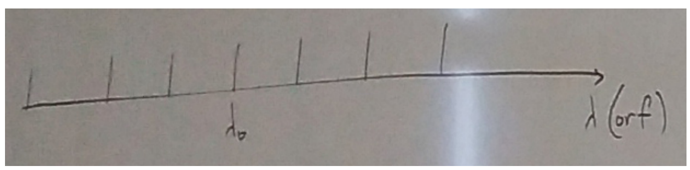

Figure 4: Images/image3.jpg

Since back and forth reflecting light which induces gain has a gaussian spectral distribution, therefore the induced gain function also has a gaussian distribution.

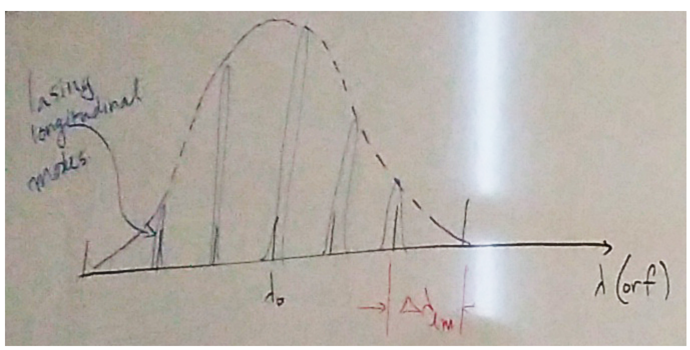

Figure 5: Images/image4.jpg

Example: For an AlGaAs LD with $\lambda_0 = 0.82um, L = 300um$, and a gain spectral width of $\Delta G_\lambda = 3nm$

Find: (a) spacing between longitudinal modes:

$$\Delta\lambda_{lm} = \frac{\lambda_0^2}{2Ln} = \frac{(}{0}.82 * 10^{-6}m)^2/(2(300 * 10^{-6}m)(36)) = 3.113 * 10^{-10}m$$

(n from table 2-1; n = 3.6)
$\boxed{(\Delta\lambda)_{lm} = 0.3113nm}$
(b) Total number of losing modes.

$$= \Delta G_\lambda / (\Delta\lambda)_{lm}) = 3nm/(0.311nm)$$

$\boxed{= 9.637 \rightarrow 9modes}$

1.2 Intensity Modulation of LD

Since lasing occurs for $I \geq I_{th}, I_{dc}$ is needed for both Digital and analog modulation.

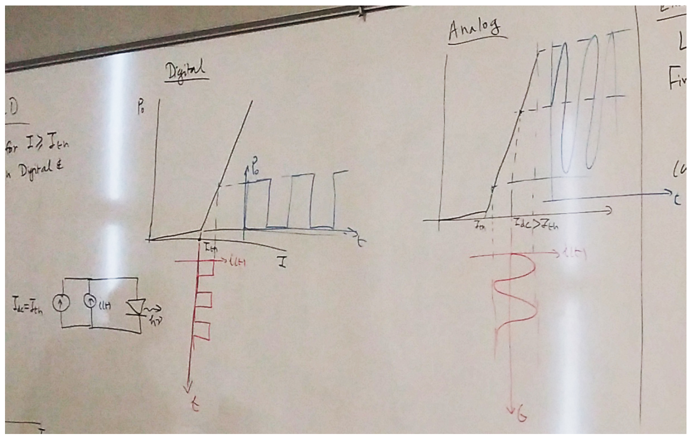

Figure 6: Images/image5.jpg

Threshold Current has a positive temperature coefficient. i.e. as temp increases, then I threshold I_{th} increases.

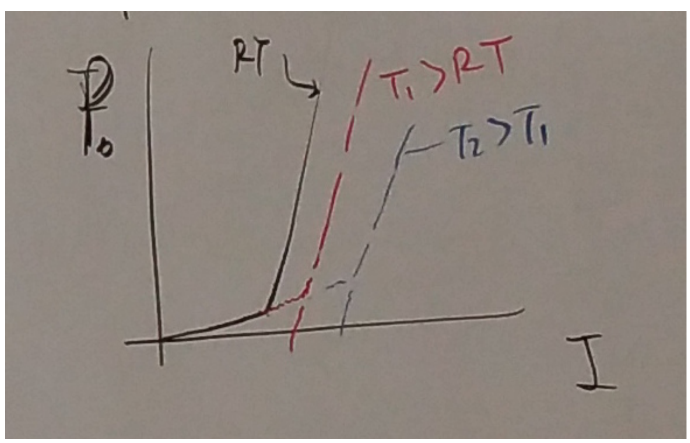

Figure 7: Images/image6.jpg

Optical gain phenomenon is used to make 1) S/C optical amplifiers (SOA; Semiconductor optical amplifier) and 2) Fiber amplifier (more popular) (EDFA).

1.3 Erbium Doped Fiber Amplifier (EDFA)

Core of fiber is doped with erbium (Er). Er is a rare earth element, with energy levels that can absorb incident radiation at $\boxed{\lambda = 1480, 980nm}$ and produce emission near 1550nm. Light source that is used to excite ion from ground level to higher energy levels is called PUMP SOURCE.

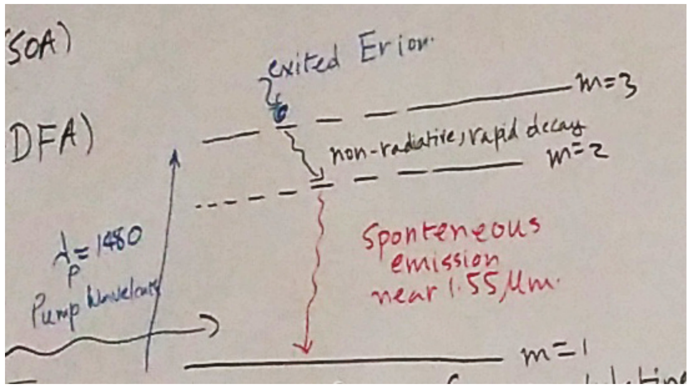

Figure 8: Images/image7.jpg

This provides amplification for a modulating signal on an incident carrier wave near $\lambda = 1.55um$. Implementation:

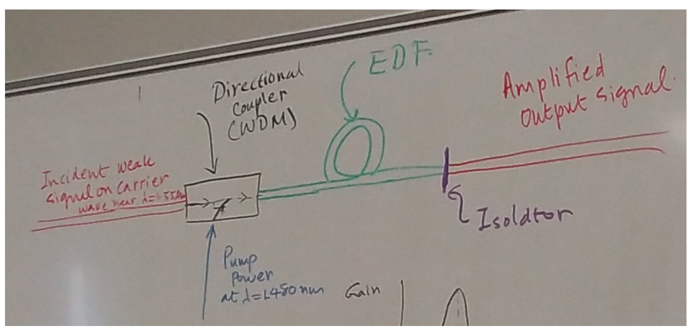

Figure 9: Images/image8.jpg

It's better to operate in flat region when having multiple channels.

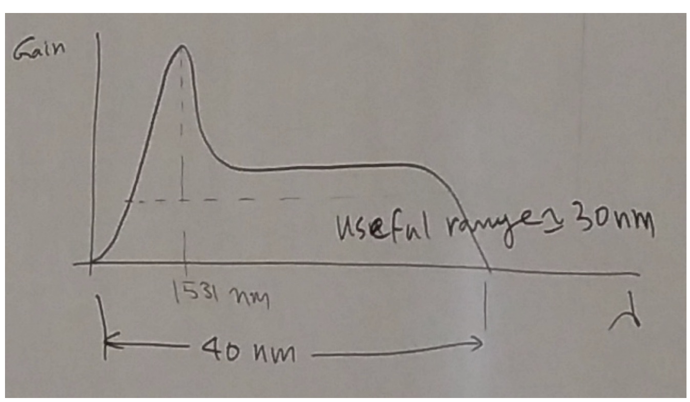

Figure 10: Images/image9.jpg

Once the attenuation for this system reached a certain point, it was adopted over electrical domain amplifiers.

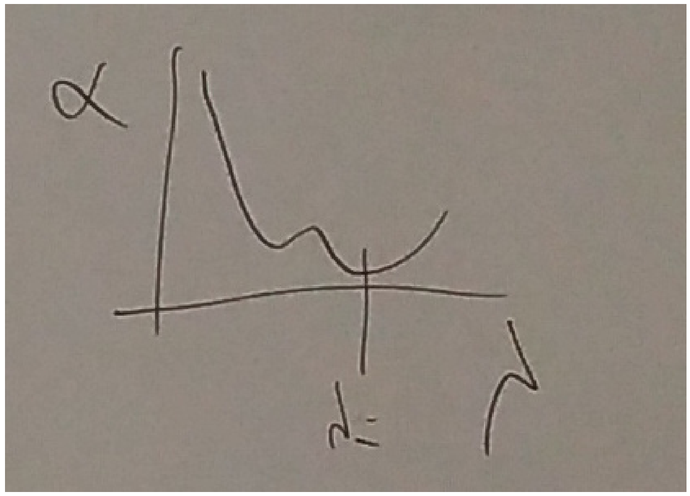

Figure 11: Images/image10.jpg

3/12 Erbium Doped Fiber Amplifier (EDFA) Continued

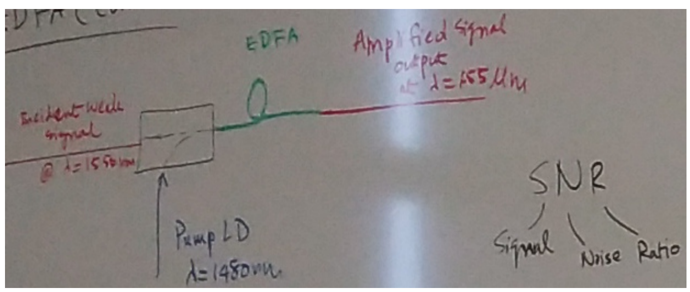

Figure 12: Images/image11.jpg

Gain of amplifier increases as Pump Power, P_P increases. G increases initially at a rate of $\frac{5-dB}{1-mWofpumppower}$, then the rate slows and Gain saturates.

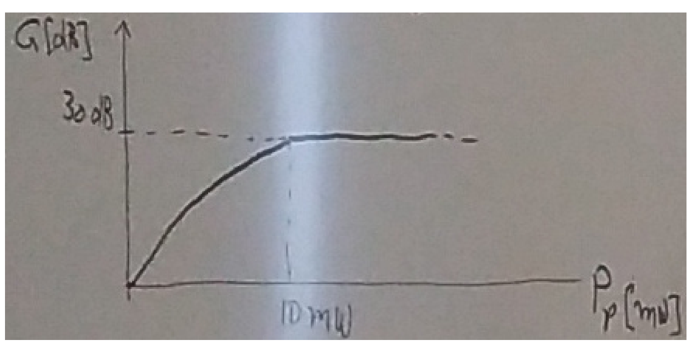

Figure 13: Images/image12.jpg

Any amplifier: (Amplifies incident signal) + (Amplifies incident noise) + (Adds amplifier own noise) This effects (S/N; signal noise ratio) at output, where

$$\frac{S}{N} = \frac{< Avg.SignalPower >_{elec}}{< Avg.NoisePower >_{elec}}$$

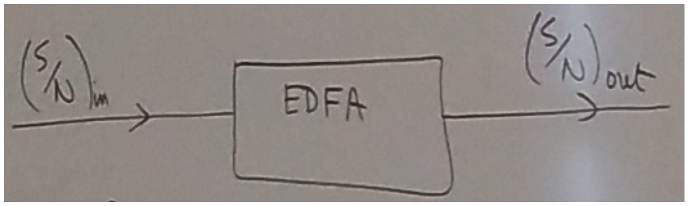

Figure 14: Images/image13.jpg

The effect of all noise at output relative to input is described by the Noise Figure, F: $\boxed{F = \frac{(S/N)_{in}}{(S/N)_{out}}}$ which can be expressed as a ratio of powers or in dB.
Example: An EDFA has $F = 3.2$. If $(S/N)_{in} = 50dB$, calculate $(S/N)_{out}$.

$$10log_{10}[F = \frac{(S/N)_{in}}{(S/N)_{out}}]$$
$$10log_{10}[F] = 10log_{10}[(S/N)_{in}] - 10log_{10}[(S/N)_{out}]$$
$$F[dB] = (S/N)_{in}[]dB - (S/N)_{out}[dB]$$
$$3.2 = 50 - (S/N)_{out}$$

$\boxed{(S/N)_{out} = 46.8dB}$

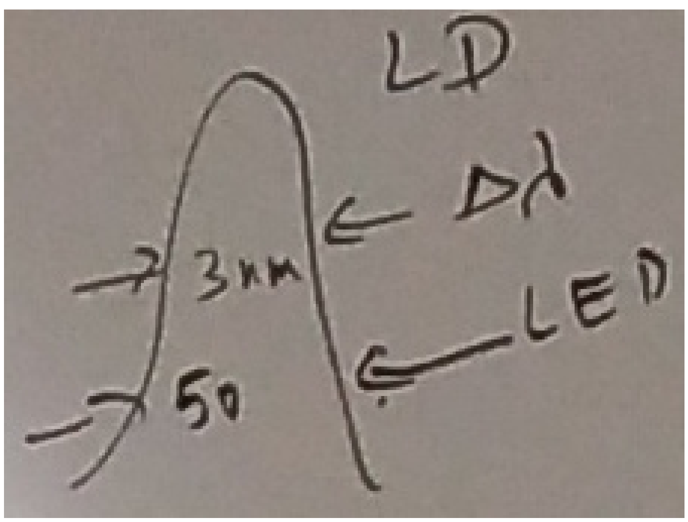

Figure 15: Images/image14.jpg

DFB laser (Δλ narrow - single mode)
VCSEL (vertical cavity surface emitting laser)
Tunable Laser (WDM; wavelength division multiplexing)

1.4 Light Detectors (Ch. 7)

Most commonly used light detectors in optical networks are based on internal photoelectric effect. They make use of the electric field "E" inherent in a S/C junction diode to produce external current.

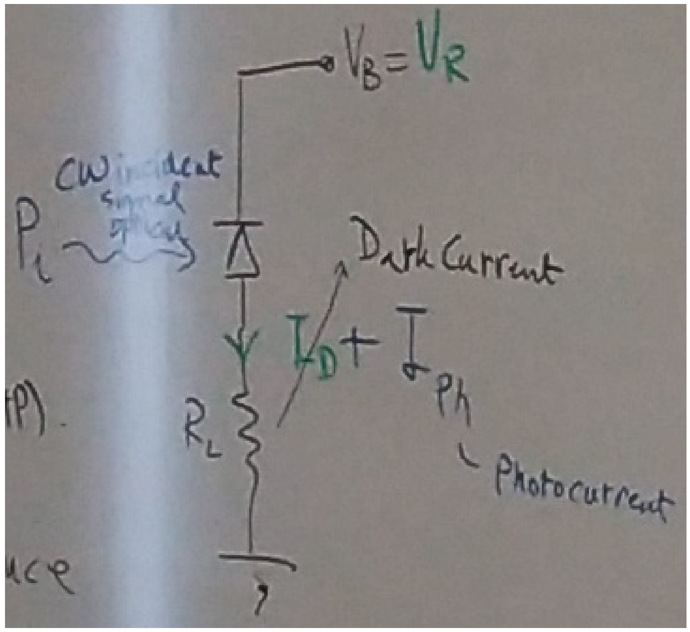

Figure 16: Images/image15.jpg

Energy absorbed from photons in an incident optical power P_i, generates electron-hole pairs (EHP).

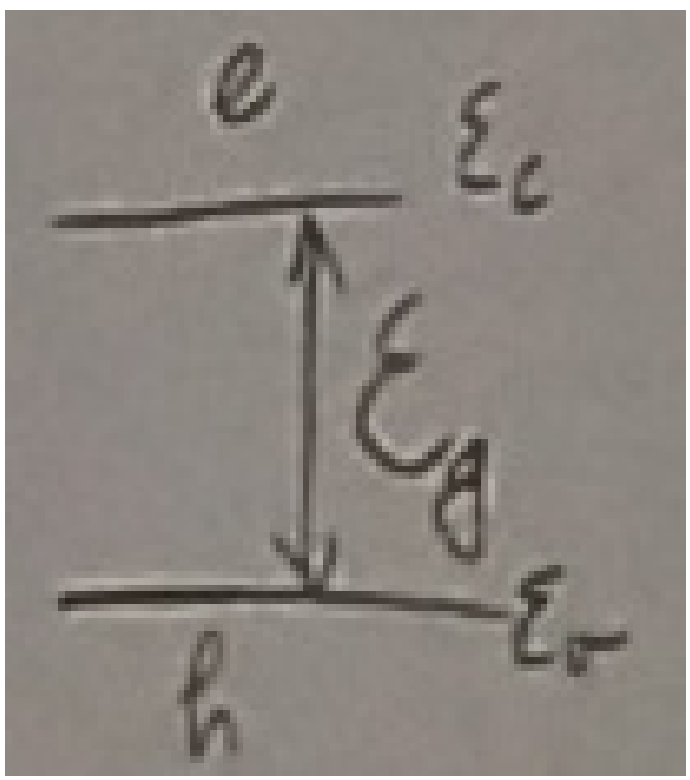

Figure 17: Images/image16.jpg

Electric field inside diode causes drift of generated carriers and produce external current, I_{ph}, if $\mathcal{E}_{ph} \geq \mathcal{E}_g$.

However not all EHP's contribute toI_{ph}. The fraction that contributes is described by Quantum Efficiency:

$$\eta = \frac{number of EHP generated/s that contribute to I_{ph}}{totem of incident photons per sec}$$

Light detectors are characterized by
1) Responsively, ρ
2) Spectral Range [i.e. useful λ range]
3) Speed of Response(i.e. rise/fall time, How fast?)
Responsivity, ρ

$$\rho = \frac{I_{ph}}{P_i}$$

$$P_i = (\text{number of photons incident/sec})\text{x}(\text{Energy/photon} = hf = \frac{hc}{\lambda})$$

$$(\text{number of photons incident/sec}) = \frac{P_i\lambda}{hc}$$

$$\text{Using: } \eta : (\text{num of EHP generated/sec} = \eta(fracP_i\lambda hc) = \eta\frac{P_i\lambda}{?}$$

$$\rightarrow I_ph = e(\text{number of EHP generated/sec})$$

$$I_{ph} = \frac{\eta e P_i \lambda}{hc}$$

$$\rightarrow \rho = \frac{I_{ph}}{P_i}$$

$\boxed{\rho = \frac{e\eta\lambda}{hc}}$ or $\rho = \frac{\eta\lambda}{1.24}[um]$

This implies ρ increases as λ increases. However not indefinitely, but it drops sharply as λ increases. Why? This happens because absorption coefficient of S/C material depends on λ. Hence η must be optimized. For max ρ, η must be optimized. For this examine depletion region in S/C pn diode.

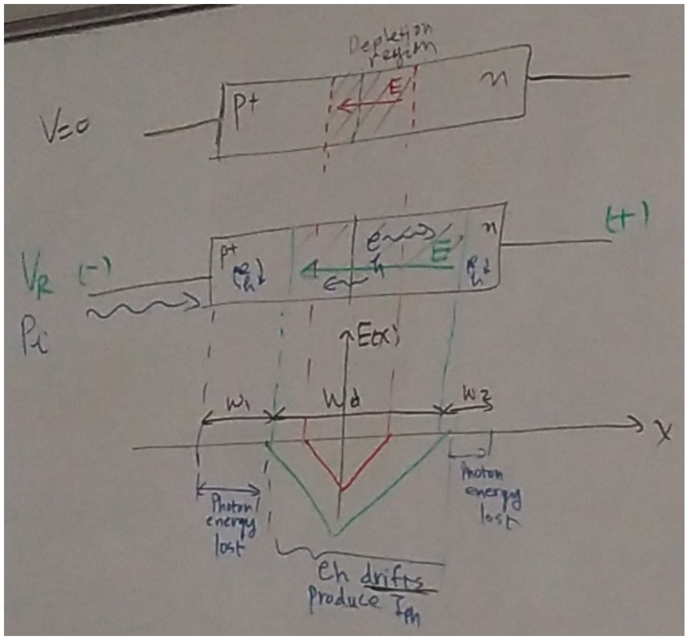

Figure 18: Images/image17.jpg

$$\rightarrow \eta = (1-R)e^{-\alpha W_1}[1-e^{-\alpha W_d}]$$

1) Use antireflection coating to reduce R
2) Make W_1 short
3) Make W_d long
4) Choose material with high α value for operating λ

$$\rho = \frac{\eta\lambda}{hc}$$

Note: α drop rate is low initially as λ increases, then drops sharply and η decreases.

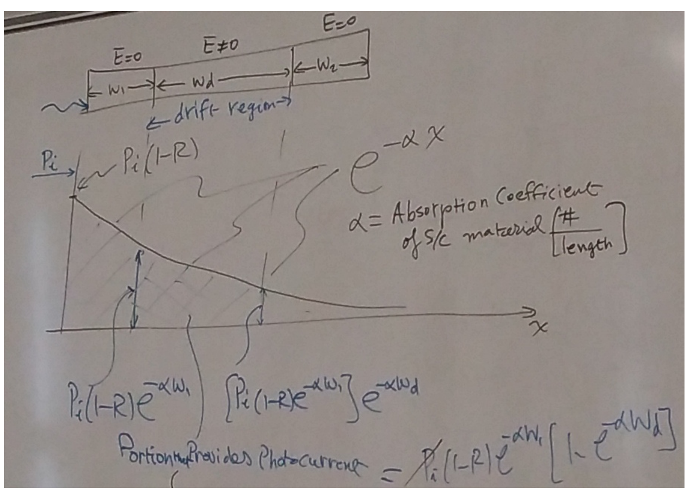

Figure 19: Images/image18.jpg

$$\lambda = 0.8um \text{ for Si or 1.555um for Ge (from Table 7.1)}$$

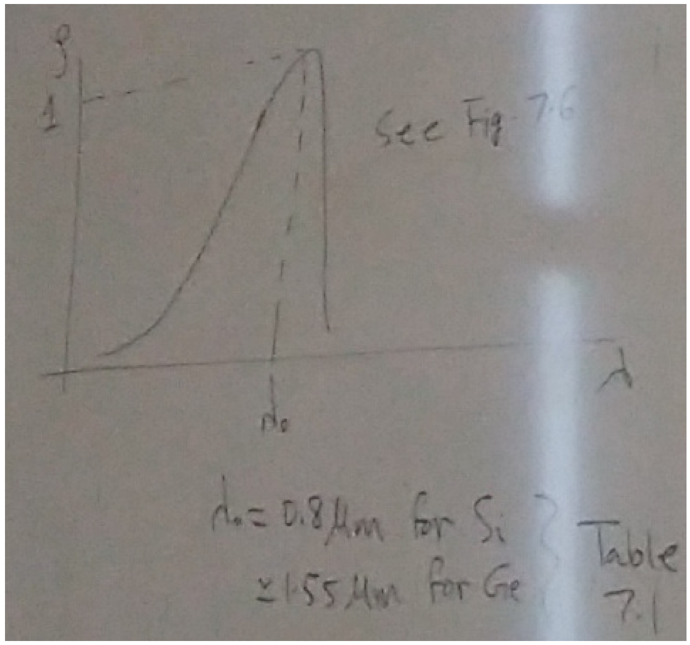

Figure 20: Images/image19.jpg

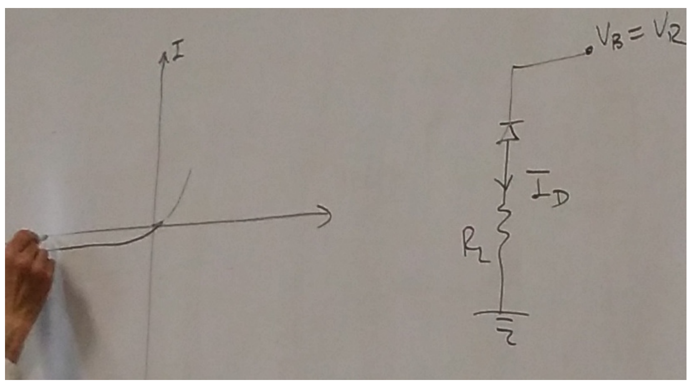

Figure 21: Images/image20.jpg

3/24 - Photodiode Continued Receptivity

$$\rho = \frac{I_{ph}}{P_i} \rightarrow I_{ph} = \rho P_i$$

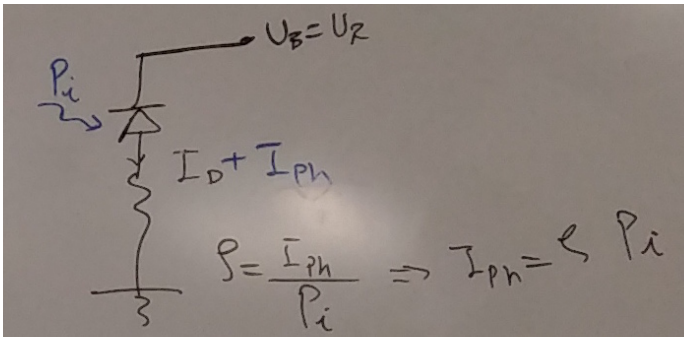

Figure 22: Images/image21.jpg

1.5 Dynamic Range of Photodiode

Dynamic Range is the range for incident optic power, P_i, over which the photodiode response current, I_{ph}, shows linear variation with P_i, before saturation.

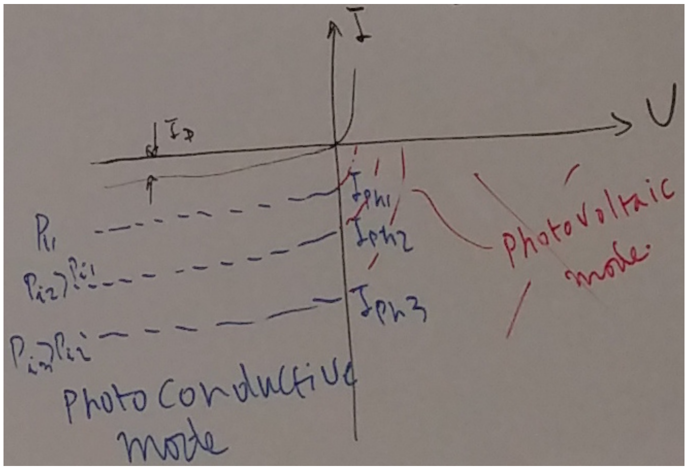

Figure 23: Images/image22.jpg

Variation with P_i, before saturation. As I_{ph} saturates, V_0 across R_L also saturates.

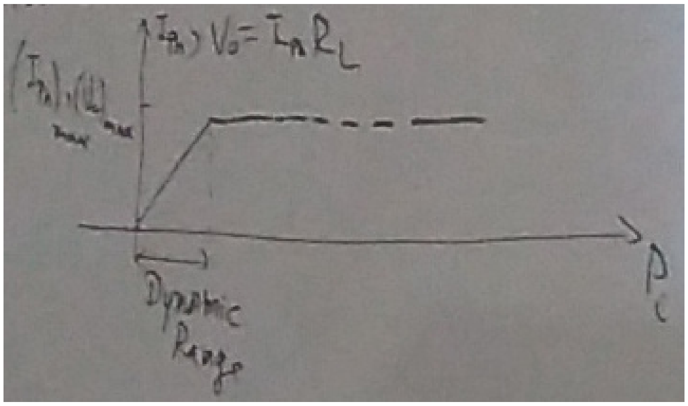

Figure 24: Images/image23.jpg

From front-end of RX (i.e. Photodiode reverse biased $+R_L$)

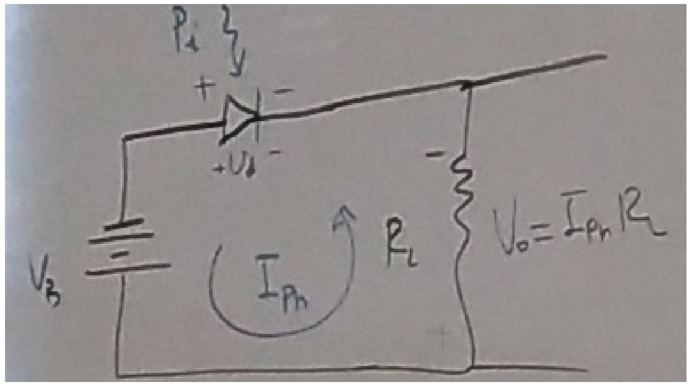

Figure 25: Images/image24.jpg

At saturation:

$$v_d = 0$$

$$KVL : \sum V = 0 \rightarrow V_B - I_{ph} R_L + v_d = 0$$

$$\text{At Saturation: } v_d = 0$$

or

$$(I_{ph})_{max} = \frac{V_B}{R_L} = I_{saturation}$$

$$(V_0)_{max} = (I_{ph})_{max} R_L$$

Example: For a photodiode with $v_B = -20V, \rho = \frac{1}{2} x \frac{A}{W?N}, R_L = 1M\Omega(10^6\Omega)$. Find Dynamic Range: Assume Ideal Diode (i.e. $R_R = \infty, R_F = 0 \rightarrow I_F = \infty, I_R = 0$)

$$(I_{ph})_{max} = \frac{V_B}{R_L} = \frac{-20}{10^6\Omega} = -20uA$$

$$(V_0) = (I_{ph})_{max} R_L = (20x10^{-6}A)(10^6\Omega) = 20V$$

$$\text{From } \rho = \frac{I_{ph}}{P_i}$$

$$(P_i)_{max} = \frac{(I_{ph})_{max}}{\rho} = \frac{20x10^{-6}}{1/2} = 40uW$$

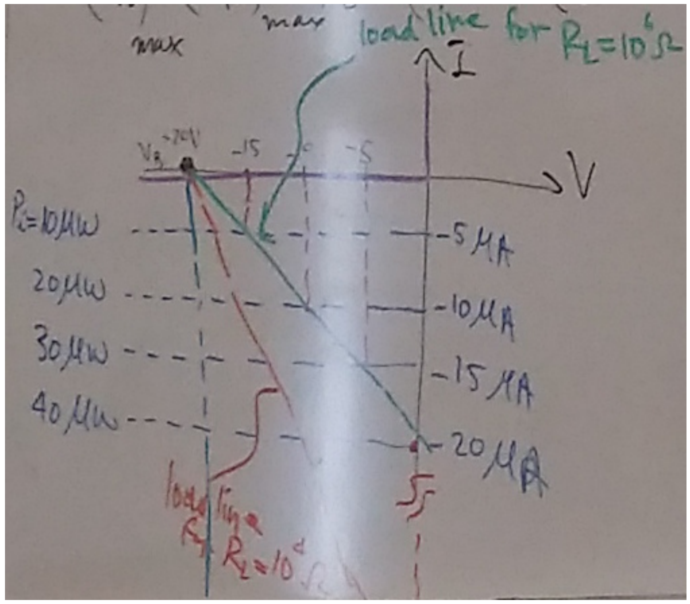

Figure 26: Images/image25.jpg

If $R_L = 10^4\Omega$

$$\rightarrow (I_{ph})_{max} = \frac{V_B}{R_L} = \frac{-20V}{10^4} = -2x10^{-3}A = -2mA = -2000uA$$

$$V_{max} = (I_{ph})_{max}R_L = (2mA)(10^4\Omega) = 20V$$

For $(I_{ph})_{max} \rightarrow \infty$, need $R_L = 0$. This could be realized using an op-amp of high-gain with feedback resistor,R_F (Input impedance of op-amp = 0).

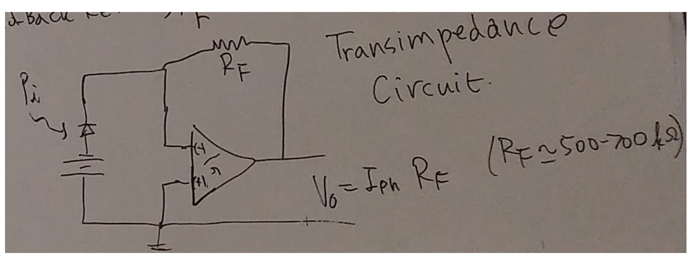

Figure 27: Images/image26.jpg

Book equations ignore regions of diode where light doesn't generate current. Over simplified, don't use for homework.
For optimizing Quantum efficiency η, recall:
W_d must be long
W_I must be short

A diode structure that fulfills these conditions is pin diode.

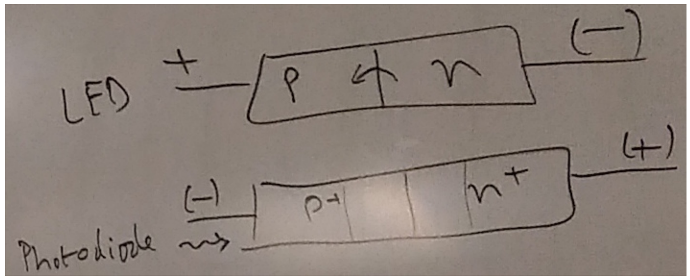

Figure 28: Images/image27.jpg

$$R = \frac{1}{\sigma}\frac{\rho}{A}$$

image To ensure maximum drift velocity, v_d, a small reverse voltage, V_R, can be applied (not necessarily needed).
Transit time for EHP to drift through $E \neq 0$ layer is

$$\tau_t = \frac{W_d}{v_d}$$

Speed of Response:
3 time factors that influence photodiode speed of response:
1) Transit time, τ_t
2) Diffusion time, τ_d
3) RC time constant, τ_{RC}
τ_t dominates speed of response, but text book ignores τ_t, τ_d. It only uses τ_{RC} based on equation derived for LED. i.e.:

$$\text{eq(7.2)}\ (f_{3-dB})_{elec} = \frac{0.35}{t_r}$$
$$\text{eq(7.15)}\ t_r = 2.197RC$$

image

$$e^{-\alpha x}\text{ignored in text}$$
$$\text{Furthermore, text says } 2.197RC \leq \frac{t_r}{4} \text{ which does not hold}$$
$$\tau_{RC} = RC$$

Actually:
For step input $P_i : t_r > 2.197RC$.
For Analog modulated incident P_i:

$$I_{ph}(t) = I_{ph}[1 + m\frac{sin(\pi f_m \tau_t)}{\pi f_m \tau_t} sin(\omega_m t - \tau_t/2)]$$
$$I_{ph} = \rho P_{dc}, \frac{sin(\pi f_m \tau_t)}{\pi f_m \tau_t} = \frac{1}{\sqrt{2}}$$

$$\rightarrow (f_{3-dB})_{elec} = \frac{0.44}{\tau_t}$$

Taking into consideration $e^{-\alpha x}$ factor which delays current response:

$$\rightarrow (f_{3-dB})_{elec} = \frac{0.55}{\tau_t}$$

$$\text{where} \tau_t = \frac{W_d}{v_d = 10^5 m/s = 10^7 cm/s}$$

However, this can be obscured by

$$(f_{3-dB}) = \frac{1}{2\pi RC}$$

due to RC time constant.

Example: Front end of Rx contains Si pin photodiodede of $W_i = 20um$, junction area $= 0.2mm^2$. and $R_L = 10k\Omega$. (a) Compare τ_t to τ_{RC} , (b) Comment on f_{3-dB}, for Si: $\epsilon_r = 11.8$

$$\tau_t = \frac{W_d \approx W_i}{v_d} = \frac{20x10^{-6}m}{10^5 m/s} = 0.2ns$$

$$\tau_{RC} = RC = (10x10^3)C$$

$$C = \frac{\epsilon_0 \epsilon_r A}{W_i} = \frac{(8.854x10^{-12}F/m)(11.8)(0.2mm^2x(10^{-3}m/mm)^2)}{20x10^{-6}m} = 1.0443x10^{-12}F$$

$\boxed{\tau_{RC} = (10^4)(1.0443x10^{-12}) = 10.443ns}$ for $\tau_t << \tau_{RC}$