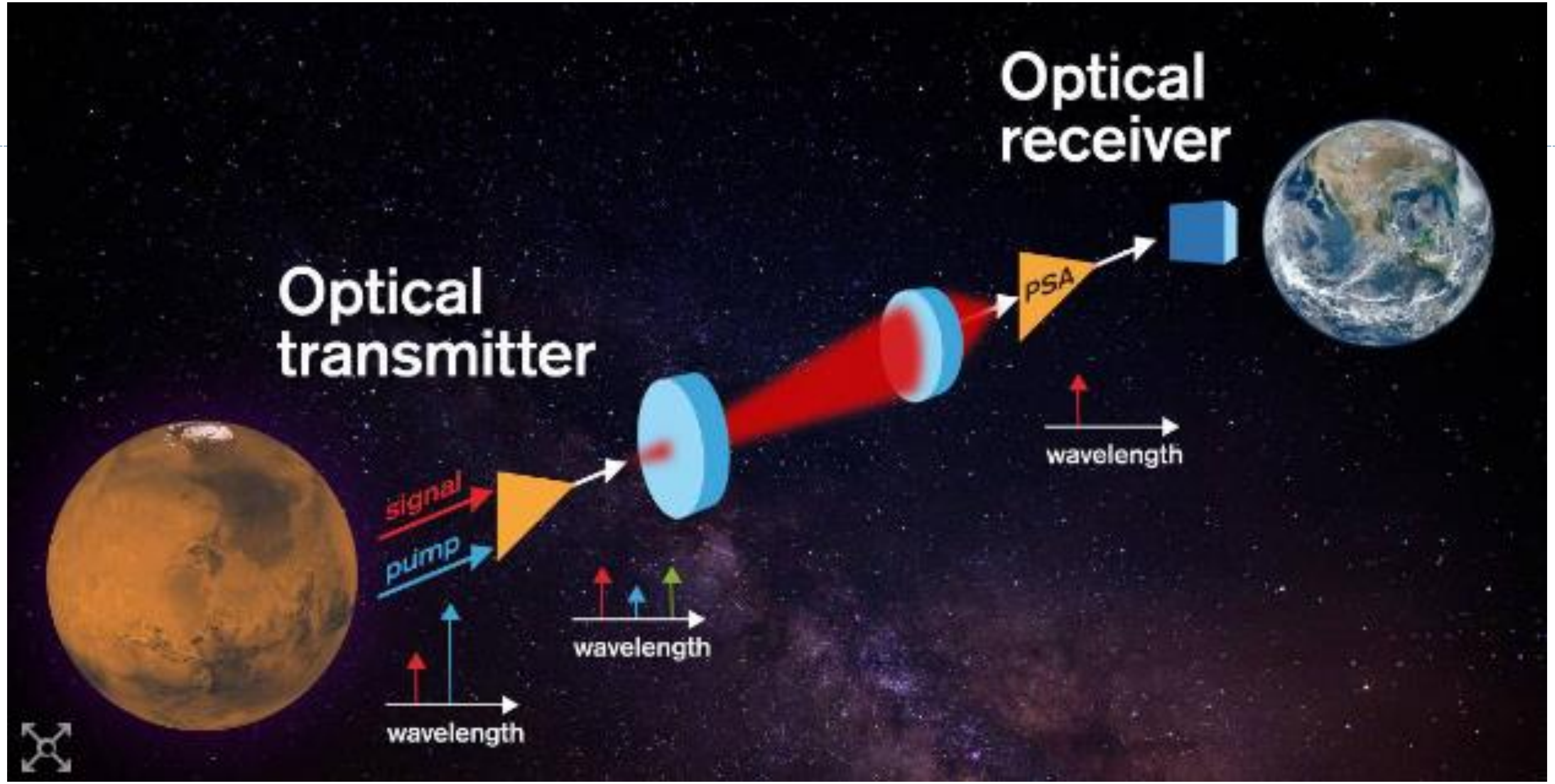
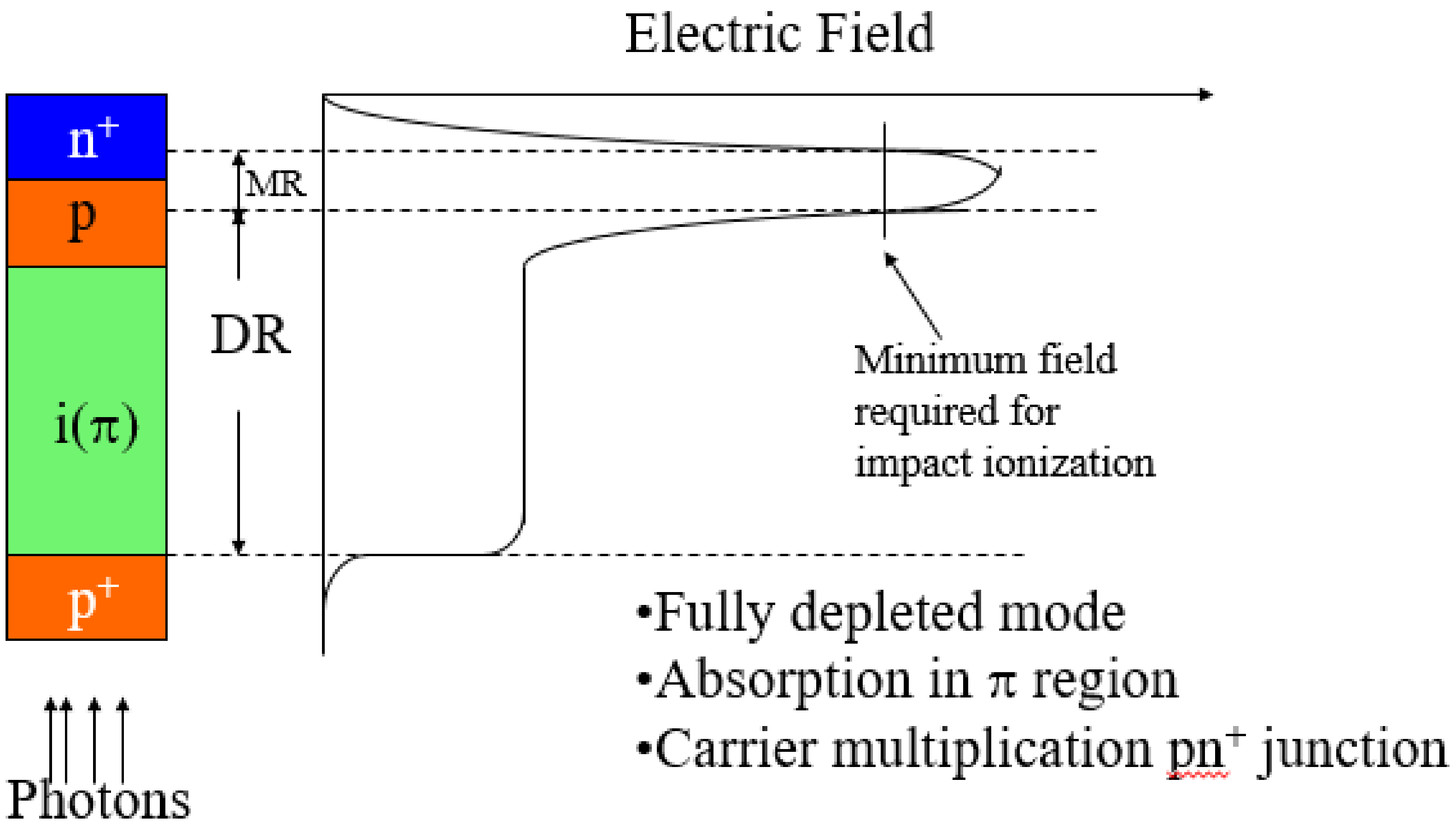


Module – 4
Optical Receivers

Avalanche Photodiode Diode(APD)

- Receiver sensitivity
- Impact ionization
- Avalanche multiplication
- Reach-through construction

p+πpn+ reach-through structure (RAPD)



Carrier Multiplication

- Internal amplification

- Thermal noise component reduced

- Ionization rate : average number of e-h+ pairs created by a carrier / unit distance
  - $k = \beta/\alpha$; $\beta \rightarrow h^+$, $\alpha \rightarrow e^-$;
  - Low noise & high GBP : $k \rightarrow 0$ 'or' ∞ (Eg. Si)

- Average Multiplication $M = I_M / I_p$

- $\Re_{APD} = (\eta q / h\nu) M = \Re_0 M$

unity gain responsivity

Numerical Problem

- A silicon APD has a quantum efficiency of 65 % at a wavelength of 900 nm. Suppose 0.5 μW of optical power produces a multiplied photocurrent of 10 μA. Find the multiplication factor M.

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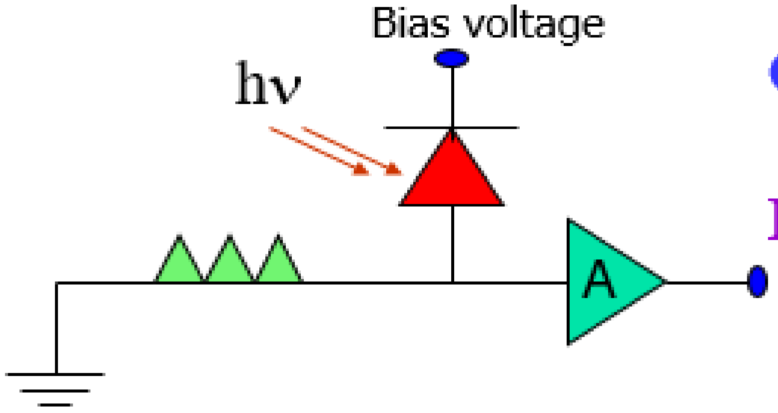
$$I_p = RP_0 = \frac{\eta q}{h\nu} P_0 = 0.235\mu A$$

$$M = \frac{I_M}{I_P} = 43$$

Sensitivity (minimum detectable optical power)

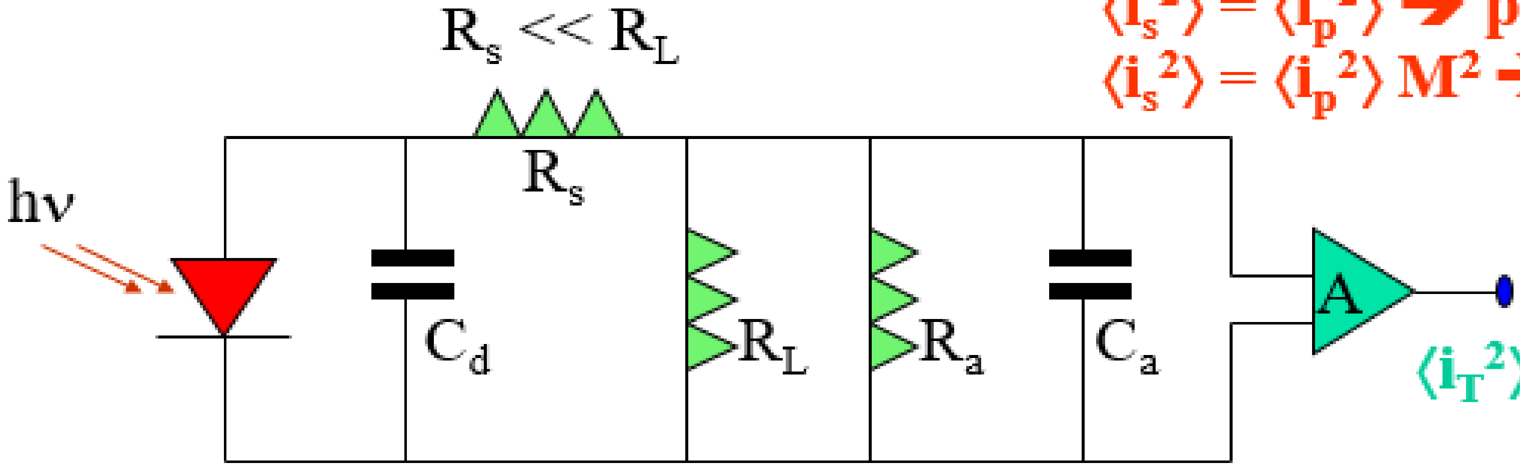


Output SNR $\rightarrow$ $\dfrac{\textbf{Signal power from photocurrent}}{\textbf{PD noise power} + \textbf{Amp. Noise power}}$

$i_{ph}(t) = I_p + i_p(t)$

$\langle i_s^2 \rangle = \langle i_p^2 \rangle \rightarrow$ pin PD

$\langle i_s^2 \rangle = \langle i_p^2 \rangle M^2 \rightarrow$ APD



$R_a >> R_L$

$\langle i_T^2 \rangle = \dfrac{4K_BTB}{R_L}$

Photodetector Noises

- Quantum noise / shot noise

- No. of photons of particular λ arriving at detector surface -> poisson process

$$\langle i_Q^2 \rangle = 2qBI_p \rightarrow \text{pin PD}$$

- Noise due to random gain mechanism (APD)

  - No. of secondary electrons generated per primary photoelectron -> random process

$$\langle i_Q^2 \rangle = 2qBI_p M^2 F(M) \rightarrow \textbf{excess noise factor}$$

$$F(M) \rightarrow \frac{\text{Actual noise generated}}{\text{Noise under constant multiplication}} \sim M^x \; (0 < x < 1)$$

Photodetector Noises

- Dark current noise
- Bulk dark current noise – thermally generated / background radiation within the bulk of the device

$$\langle i_{DB}^2 \rangle = 2qBI_D \quad \rightarrow \text{pin PD}$$

$$\langle i_{DB}^2 \rangle = 2qBI_D M^2 F(M) \quad \rightarrow \text{APD}$$

- Surface leakage current noise – surface defects, cleanliness, bias, etc.
- Guard ring structure

$$\langle i_{DS}^2 \rangle = 2qBI_L \quad \rightarrow \text{pin PD \& APD}$$

- Impact of increasing M on SNR (BER)

Speed of response

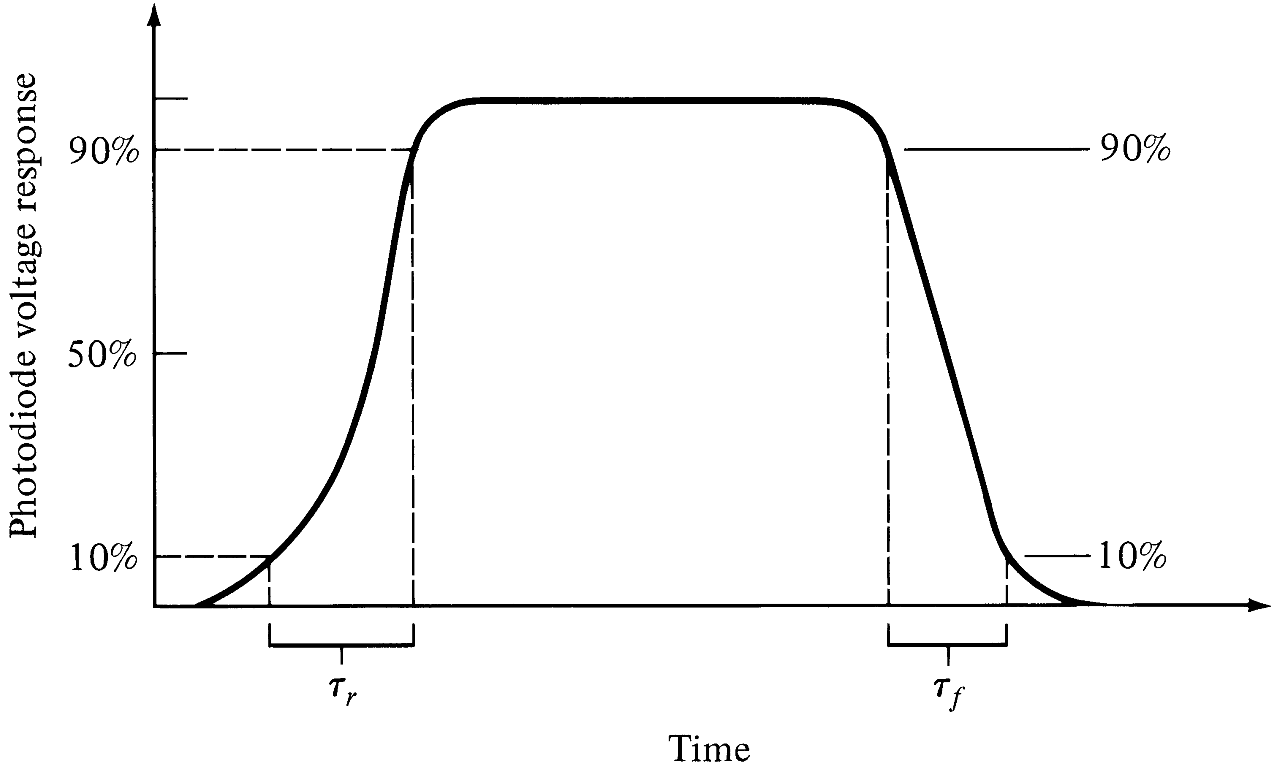
- Drift time of carriers through the depletion region
  - electron field at saturation v_d
  - $t_{drift} = w/v_d$ [Si -> 0.1 ns for $w=10\mu m$, $2x10^4$ V/cm]
- Diffusion time of carriers generated outside the depletion region
  - Slow process
- Time constant incurred by the capacitance of the photodiode with its load (junction & packaging)
  - Voltage dependant capacitance $C_j = \varepsilon_s A/w$
- PD as RC LPF

$$B = 1/2\pi R_t C_t$$

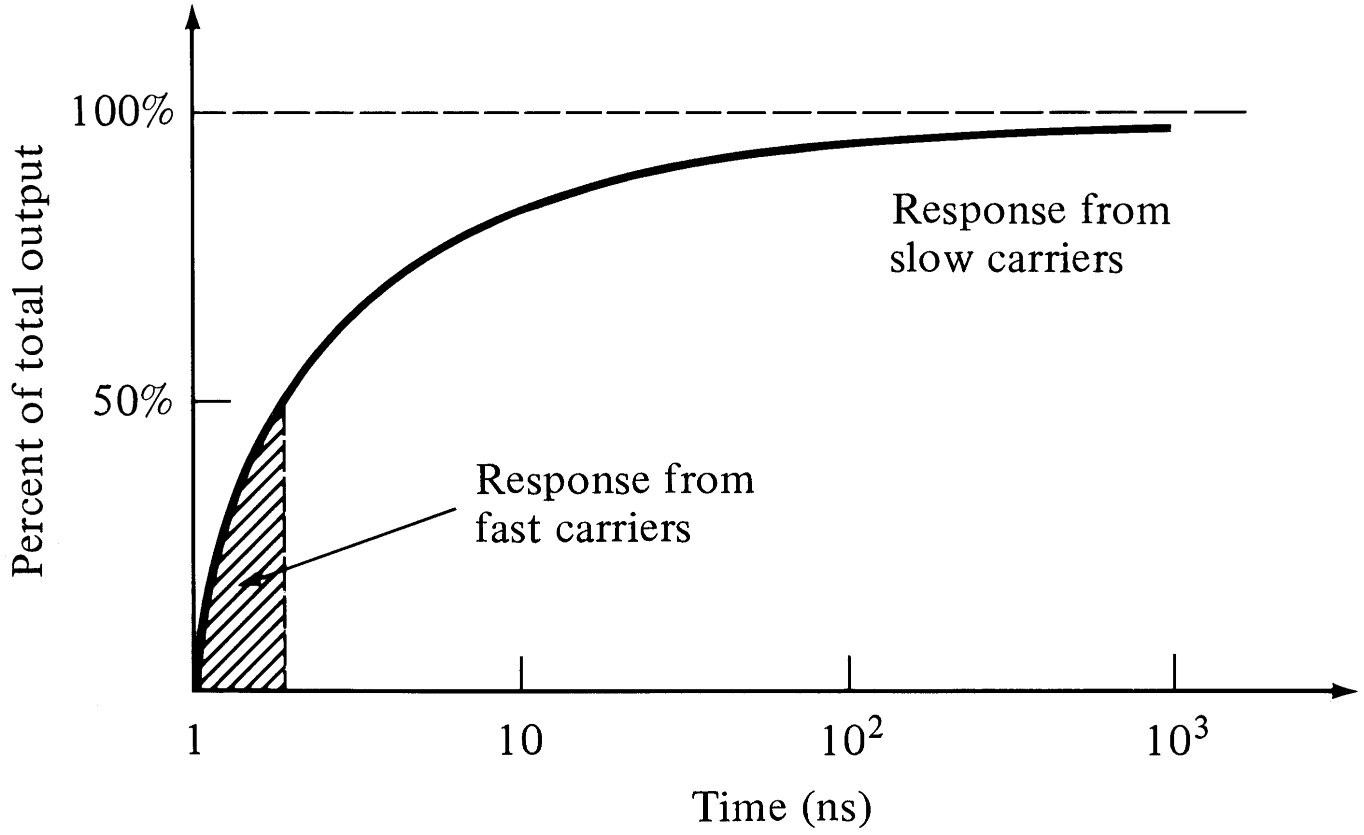
- Maximum PD 3 dB BW

$$B_m = 1/2\pi t_{drift} = v_d / 2\pi w$$

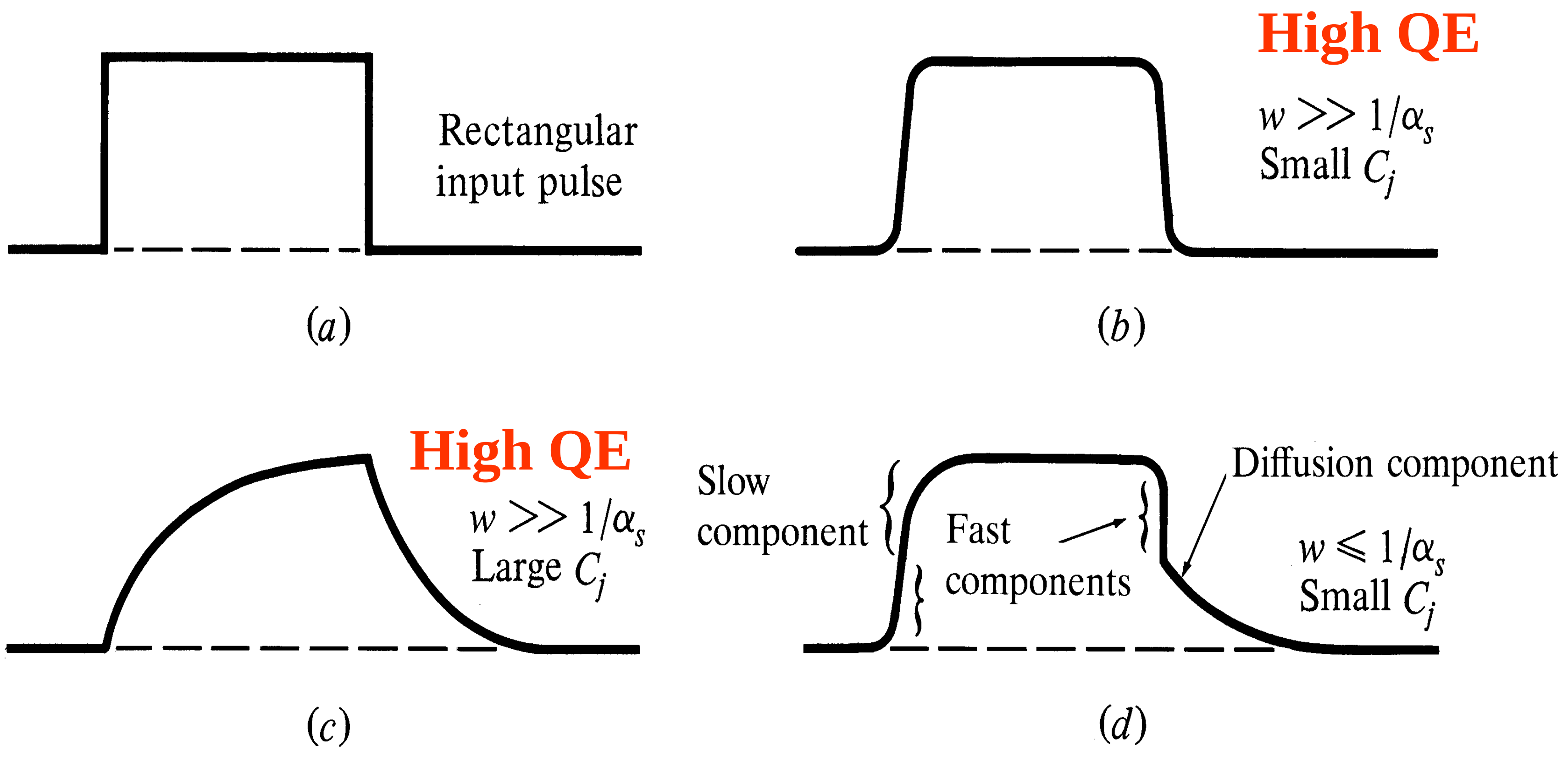
Rise and fall times



Photodiode not fully depleted



Various pulse responses



APD Vs. pin PD

- pin PD -> thermal noise - signal independent
- APD -> shot noise dominant – signal dependent noise
- APD sensitivity:
  - λ = 0.82 μm, APD 10-13 dB away from quantum limit
    pin PD 15 dB away from quantum limit
  - λ = 1.55 μm, APD 20 dB above quantum limit
    pin PD 30-32 dB over quantum limit
- APD drawbacks:
  - ➢ Fabrication difficulties & increased cost
  - ➢ Addition of noise due to gain randomness
  - ➢ Higher bias voltages
  - ➢ Variation of gain with temperature (α, β)

Numerical Problem

- If the PD capacitance is 3 pF, the amplifier capacitance is 4 pF, the load resistor is 1 KΩ and the amplifier input resistance is 1 MΩ. Calculate the value of R_T, C_T and also find the circuit bandwidth.

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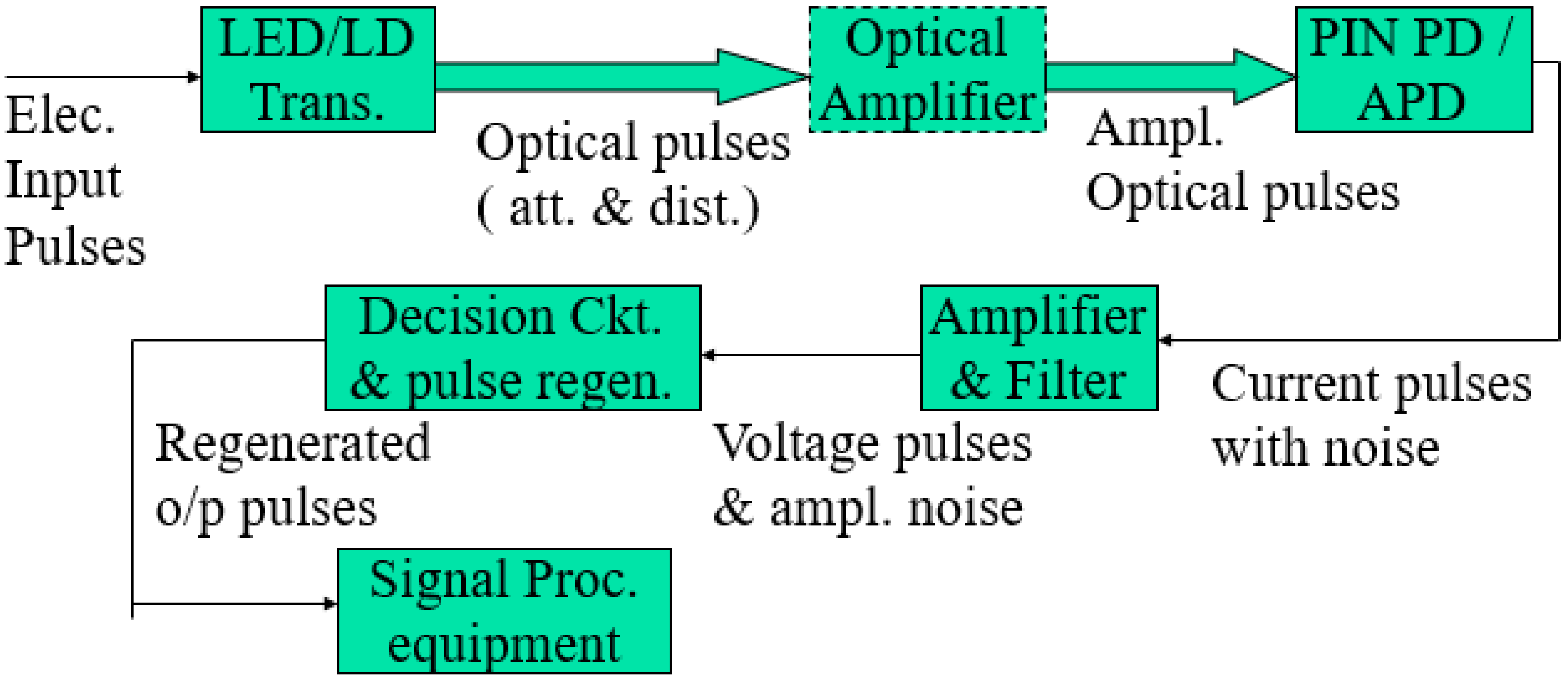
$$R_T = 1k\Omega, C_T = 7\,pF$$

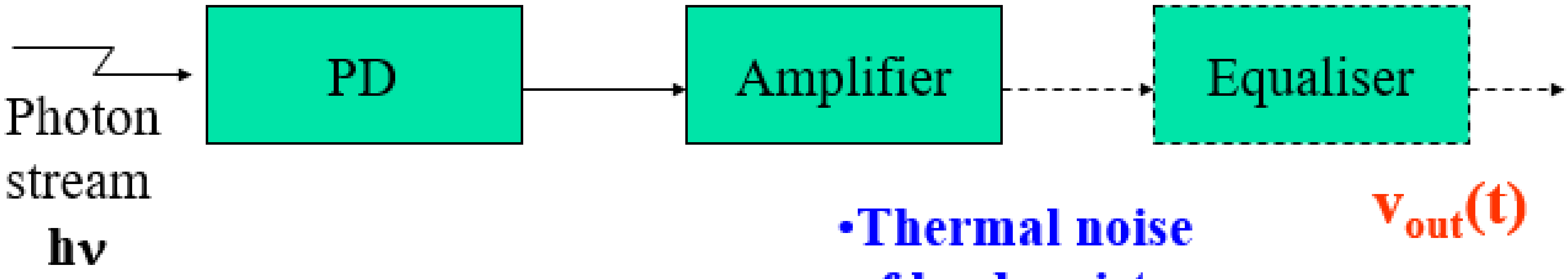
$$B = \frac{1}{2\pi R_T C_T} = 23MHz$$

Digital Signal Transmission



Signal path through an optical data link

Noise Sources



- Photon detection Quantum noise (Poisson func.)

- Bulk dark current
- Surface leakage current
- Statistical gain fluctuation (APD)
- Beat noise

- Thermal noise of load resistor
- Amplifier noise

Quantum Limit
Ideal PD -> QE = 1, dark current = 0

- Quantum limit → minimum pulse energy required for a specific error-rate performance under ideal conditions
- Primary photocurrent → time-varying Poisson process with mean
  $N' = \eta /(h\nu) \int_0^{\tau} P(t)\, dt = \eta E/(h\nu)$

  E → energy falling on the detector in the interval $(0, \tau)$

  $Pr(n) = N'^{\,n} \exp(-N')/n!$
- Error if detected as a '0' i.e. no e^-h^+ pair generated

  $Pr(0/1) = \exp(-N')$ ➔ probability of error (10^{-9})

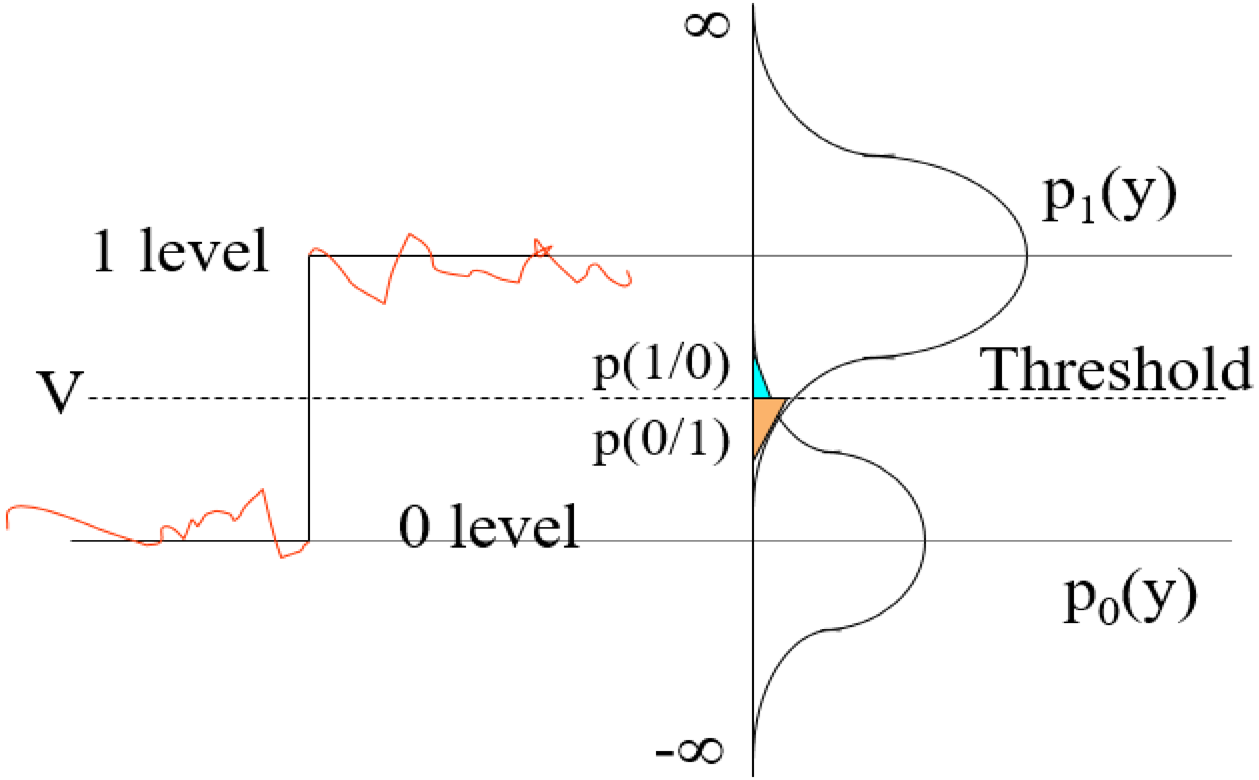
  N' ➔ 20.7 ≈ 21 photons per pulse for detection

  $E_{min} = 20.7\,(h\nu)/\eta$ ➔ $P_o = E/\tau = E\,(B/2)$

Error Probability
BER = Ne/Nt

$$v_{out}(t) = A\,M\,\Re_o\,P(t) * h_B(t) * h_{eq}(t)$$

Error in detection ➔ Noises , ISI, Non-zero extinction



$$p(1/0) = \int_{V}^{\infty} p_0(y)\,dy$$

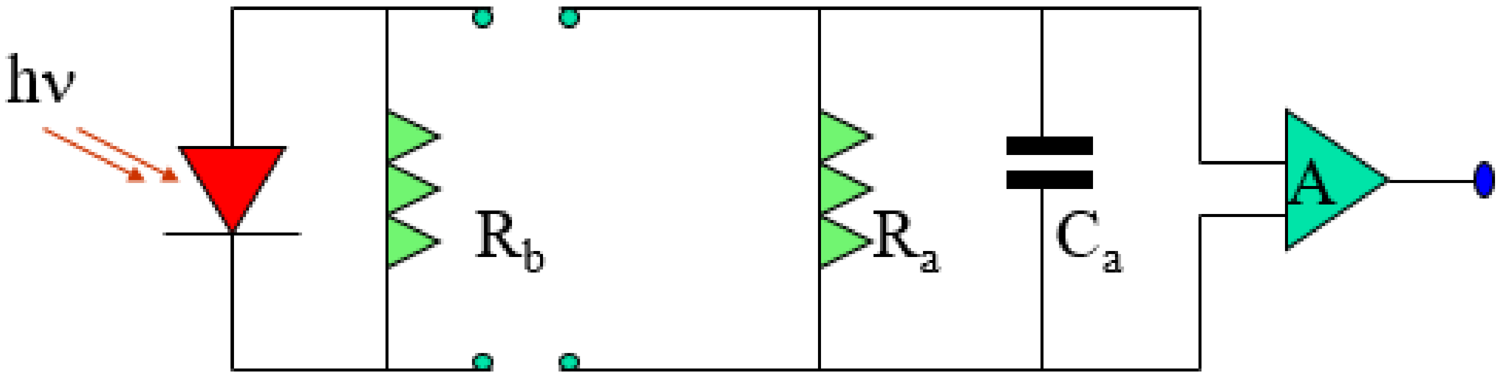
$$p(0/1) = \int_{-\infty}^{V} p_1(y)\,dy$$

$$P_e = p(1)\,p(0/1) + p(0)\,p(1/0)$$

Pre-amplifiers

- Preceeds the equalizer
- Maximize sensitivity
  - by minimising noise
  - maintaining suitable bandwidth
- Possible receiver structures
  - Low impedance front end
  - High impedance front end
  - Transimpedance front end

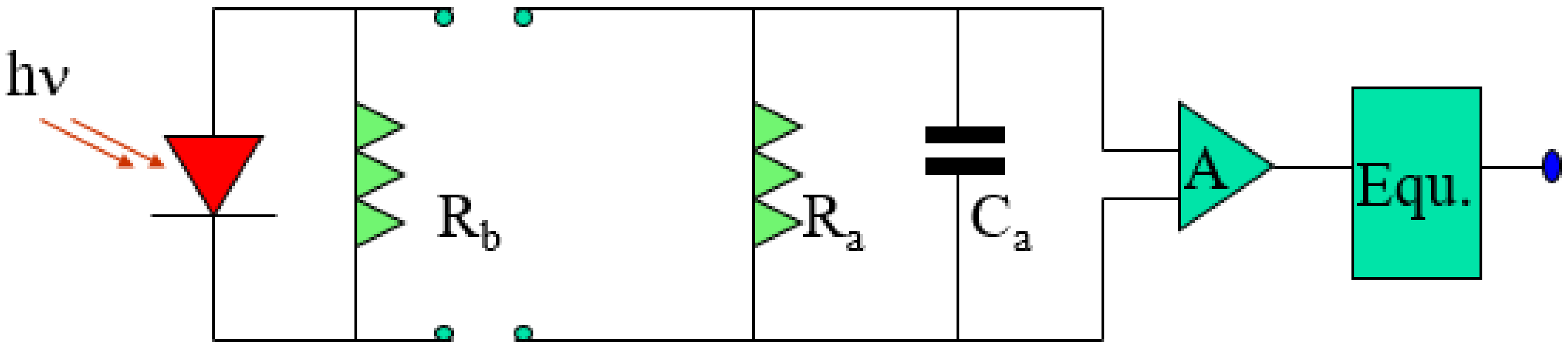
Low impedance pre-amplifier



$$R_L = R_b \parallel R_a$$

- PD operates into a low-impedance amplifier (i.e. 50 *ohms*)
- Bias / load resistance used to match amplifier i/p impedance
- Bandwidth maximized due to lesser R_L
- Receiver sensitivity is less due to large thermal noise
- Suitable only for short-distance applications

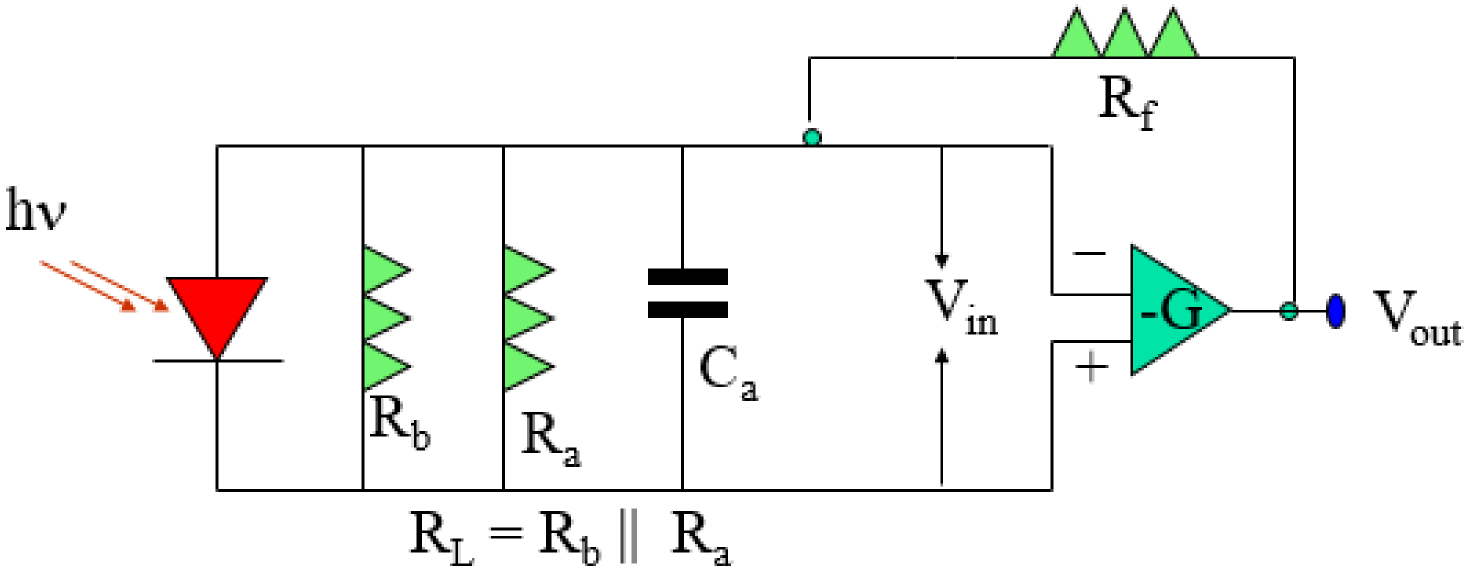
High impedance pre-amplifier



$$R_L = R_b \,||\, R_a$$

- PD operates into a high-impedance amplifier
- Bias / load resistance matched to amplifier i/p impedance
- Receiver sensitivity is increased due to lesser thermal noise
- Degraded frequency performance
- Equalization is a must
- Limited dynamic range

Transimpedance pre-amplifier



- PD operates into a low-noise high-impedance amplifier with (-)ve FB
- Current mode amplifier, high i/p impedance reduced by NFB
- Receiver sensitivity is increased due to lesser thermal noise
- Degraded frequency performance
- Equalization is a must
- Limited dynamic range

Numerical Problem

- A Silicon RAPD, operating at a wavelength of 0.80 μm, exhibits a quantum efficiency of 90%, a multiplication factor of 800, and a dark current of 2 nA. Calculate the rate at which photons should be incident on the device so that the output current after avalanche gain is greater than the dark current.

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$$I = M I_P = M \Re P_0 = M \frac{\eta q \lambda}{h c} P_0 = 2\ \text{nA}$$

$$\text{Photon rate} = \frac{P_0}{h c / \lambda} = \frac{I}{M \eta q} = 1.736 \times 10^{7}\ s^{-1}$$

The photon rate should be greater than $1.736 \times 10^{7}\ s^{-1}$ for the multiplied current to be greater than the dark current.

Numerical Problem

- An InGaAs pin photodiode has the following parameters at 1550 nm: I_D=1.0 nA, η=0.95, R_L=500 Ω, and the surface leakage current is negligible. The incident optical power is 500 nW (-33 dBm) and the receiver bandwidth is 150 MHz.
- Compare the noise currents.

Numerical Problem

$$i_Q = (2qI_pB)^{1/2}; \quad I_p = R\cdot P_0 = \frac{\eta\cdot\lambda}{1.24}P_0 = 1.19 \text{ A/W} \times 500 \text{ nW} = 0.6\,\mu\text{A}$$

$$i_Q = (2\times 1.6\cdot 10^{-19}\times 0.6\cdot 10^{-6}\times 150\cdot 10^{6})^{1/2} = 5.4\,\text{nA}$$

$$i_{DB} = (2qI_DB)^{1/2} = (2\times 1.6\cdot 10^{-19}\times 1\cdot 10^{-9}\times 150\cdot 10^{6})^{1/2} = 0.22\,\text{nA}$$

$$i_{DS} = (2qI_SB)^{1/2} \approx 0$$

$$i_T = \left(\frac{4kT}{R_L}B\right)^{1/2} = \left(\frac{4\times 1.38\cdot 10^{-23}\times 293}{500}150\cdot 10^{6}\right)^{1/2} = 70\,\text{nA}$$

Numerical Problem

- A digital fiber optic link operating at 850 nm requires a maximum BER of 10^{-9}. Determine the quantum limit considering unity quantum efficiency of the detector. Find the energy of the incident photons. Also determine the minimum incident optical power that must fall on the photodetector to achieve a BER of 10^{-9} at a data rate of 10 Mbps for a simple binary –level signaling scheme.

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$$P_r(0) = \exp(-\bar{N}') = 10^{-9}$$

$$\bar{N}' = 9 \ln 10 = 20.7 = 21 \text{ photons needed per pulse}$$

$$\text{Energy } E = \text{No. of photons} \times h\nu = 20.7 \frac{hc}{\lambda} = P_o \tau$$

$$B / 2 = 1 / \tau \text{ ; assuming unbiased data}$$

$$P_o = \frac{20.7\,(6.626 \times 10^{-34} \text{ J.s})\,(3 \times 10^{8} \text{ m/s})\,(10 \times 10^{6} \text{ bps})}{2\,(0.85 \times 10^{-6} \text{ m})}$$

$$= -76.2 \text{ dBm}$$

Numerical Problem

- Consider a digital fiber optic link operating at a bitrate of 622 Mbit/s at 1550 nm. The InGaAs pin detector has a quantum efficiency of 0.8.

- Find the minimum number of photons in a pulse required for a BER of 10^{-9}.
- Find the corresponding minimum incident power.

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- Find the corresponding minimum incident power.

$$P(n) = \overline{N}^{\,n} \frac{e^{-\overline{N}}}{n!}; \quad P(0) = e^{-\overline{N}} = 10^{-9} \Rightarrow \overline{N} = 9 \ln 10 = 20.7 \approx 21 \,\text{photons}$$

$$E = 20.7 \frac{h\nu}{\eta} = 20.7 \frac{hc}{\eta\lambda} = 20.7 \frac{1.24}{0.8 \cdot 1.55} = 20.7 \,\text{eV}$$

$$P_0 = E \frac{B}{2} = 20.7 \times 1.6 \cdot 10^{-19} \times 311 \cdot 10^{6} = 1 \,\text{nW}$$

Numerical Problem

- A high i/p impedance amplifier which is employed in an optical fiber receiver has an effective input resistance of 4 MΩ which is matched to a detector bias resistor of the same value. Determine:
- The maximum bandwidth that may be obtained without equalization if the total capacitance CT is 6 pF.
- The mean square thermal noise current per unit bandwidth generated by this high input impedance amplifier configuration when it is operating at a temperature of 300 K.
- Compare the values calculated with those obtained when the high input impedance amplifier is replaced by a transimpedance amplifier with a 100 KΩ feedback resistor and an open loop gain of 400. It may be assumed that $R_f << R_T$, and that the total capacitance remains 6 pF.

Numerical Problem

- R_T = (4 MΩ x 4 MΩ) / 8 MΩ = 2 MΩ
- BW of HIA
  - B = $1/(2\pi R_T C_T)$ = 1.33×10^4 Hz = 13 KHz
  - Mean square thermal noise current = $4KT / R_T$ = 8.29×10^{-27} A^2 / Hz
  - K=1.38*10-23
- BW of TIA
  - B = $G/(2\pi R_f C_T)$ = 1.06×10^8 Hz = 106 MHz
  - Mean square thermal noise current = $4KT / R_f$ = 1.66×10^{-25} A^2 / Hz

Noise power in TIA / Noise power in HIA = $10 \log_{10} 20$ = 13 dB

Numerical Problem

- A good silicon APD ($x=0.3$) has a capacitance of 5 pF, negligible dark current and is operating with a post detection bandwidth of 50 MHz. When the photocurrent before gain is 10^{-7} A and the temperature is 18^{o}C; determine the maximum SNR improvement between M=1 and M=Mop assuming all operating conditions are maintained.

Numerical Problem

- A good silicon APD (x=0.3) has a capacitance of 5 pF, negligible dark current and is operating with a post detection bandwidth of 50 MHz. When the photocurrent before gain is 10^{-7} A and the temperature is 18°C; determine the maximum SNR improvement between M=1 and M=Mop assuming all operating conditions are maintained.

- Max. value of $R_L = 1/2\pi C_d B = 635.5\ \Omega$
- SNR at M=1 ➔ $I_p^2 / \{2eBI_p + (4KTB/R_L)\}$

  $= 7.91 = 8.98$ dB
- $M_{op}^{2+x} = \{2eI_L + (4KT/R_L)\}/\{xe(I_p + I_D)\}$

  $= 41.54 \rightarrow F(M) = M^x \ (0 < x < 1.0)$
- SNR at $M=M_{op}$ ➔ $1.78 \times 10^3 = 32.5$ dB
- SNR Improvement → 23.5 dB

Numerical Problem

- A Si pin photodiode has a quantum efficiency of 70% at a wavelength of 0.85 mm. Calculate its responsivity.
- Calculate the responsivity of a Germanium diode at 1.6 mm where its quantum efficiency is 40%.
- A particular photodetector has a responsivity of 0.6 A/W for light of wavelength 1.3 mm. Calculate its quantum efficiency.

Numerical Problem

$$R = \frac{\eta\lambda(\mu\text{m})}{1.24} = \frac{0.7\times 0.85}{1.24} = 0.48 \text{ A/W}$$

$$R = \frac{\eta\lambda(\mu\text{m})}{1.24} = \frac{0.4\times 1.6}{1.24} = 0.52 \text{ A/W}$$

$$\eta = \frac{R\cdot 1.24}{\lambda(\mu\text{m})} = \frac{0.6\times 1.24}{1.3} = 57\%$$