BUDDHA SERIES

(Unit Wise Solved Question & Answers)

Course – B. Tech (ECE)

College – Buddha Institute of Technology

(AKTU CODE-525)

Department: Electronics and Communication Engineering

Subject: Optical Communication (BEC-057)

Faculty Name: Arun Kumar Mishra

Unit – 4

Q1. Illustrate Source to Fiber Power Launching in optical communication. [AKTU: 2023-24]

ANS:

Power Launching in Fiber

Source to Fiber Power Launching -

Launching optical power from source to fiber needs following considerings.

Fiber Parameters →
- Numerical aperture
- Core size
- Refractive index profile
- core-cladding index difference

Source Parameters →
- size
- Radiance
- Angular power distribution.

* The optical power that can couple into a fiber depends on the radiance or brightness which is given through a diode drive current. Radiance is the optical power radiated into a unit solid angle per unit emitting surface areas and is generally specified in terms of watts per square centimeter per steradian.

* A measure of amount of optical power emitted from a source that can be coupled into a fiber is usually given by the coupling efficiency η defined as -

$$\eta = \frac{P_F}{P_S}$$

Here P_F = Power coupled into the fiber

P_S = Power emitted from the light source

coupling efficiency depends on -

(i) Type of fiber that is attached to the source.

(ii) coupling process

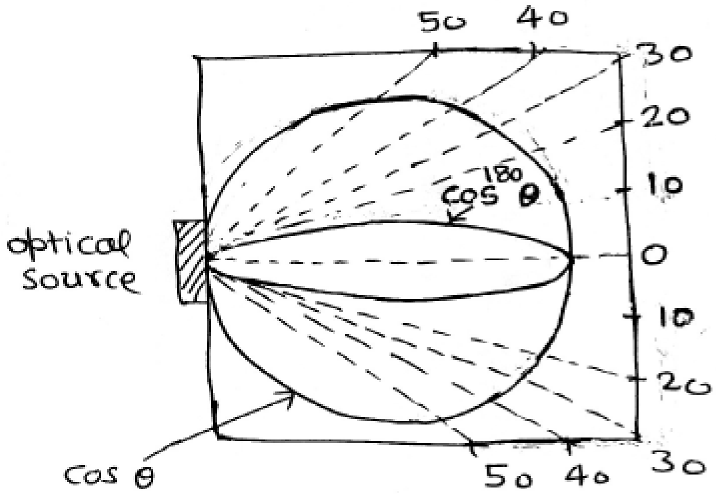
* Flylead / Pigtail — short length of optical fiber attached with the source for best power coupling configuration is known as flylead / Pigtail. Power launching from these pigtailed sources reduces to a simpler coupling optical power from one fiber to another.

Source output Pattern -

Surface-emitting LEDs are characterized by their lambertain output pattern, which means the source is equally bright when viewed from any direction. The power delivered at an angle θ measured relative to a normal to the emitting surface varies as $\cos\theta$ because the projected area of the emitting surface varies as $\cos\theta$ with viewing direction. The emission pattern for a Lambertain source is given by,

$$B(\theta, \phi) = B_0 \cos\theta$$

where B_0 = Radiance along the normal to the radiating surface.



Radiance Patterns for a Lambertain source and the lateral output of highly directional laser diode. Both sources have B_0 normalized to unity.

Power Launching versus wavelength -

* optical power only depends on the radiance and not on the wavelength of the mode. For a graded index fiber number of modes is given by

$$M = \frac{\alpha}{\alpha+2}\left(\frac{2\pi a n_1}{\lambda}\right)^2 \Delta \quad \text{———} (1)$$

where, a = Radius of the core
α = Index Profile
Δ = Relative refractive index difference
n_1 = Refractive index of core
λ = wavelength of light

* The relative power per mode from a source at a particular wavelength is given by

$$\frac{P_s}{M} = B_o \lambda^2$$

where B_o = Radiance along the normal to the radiating surface.

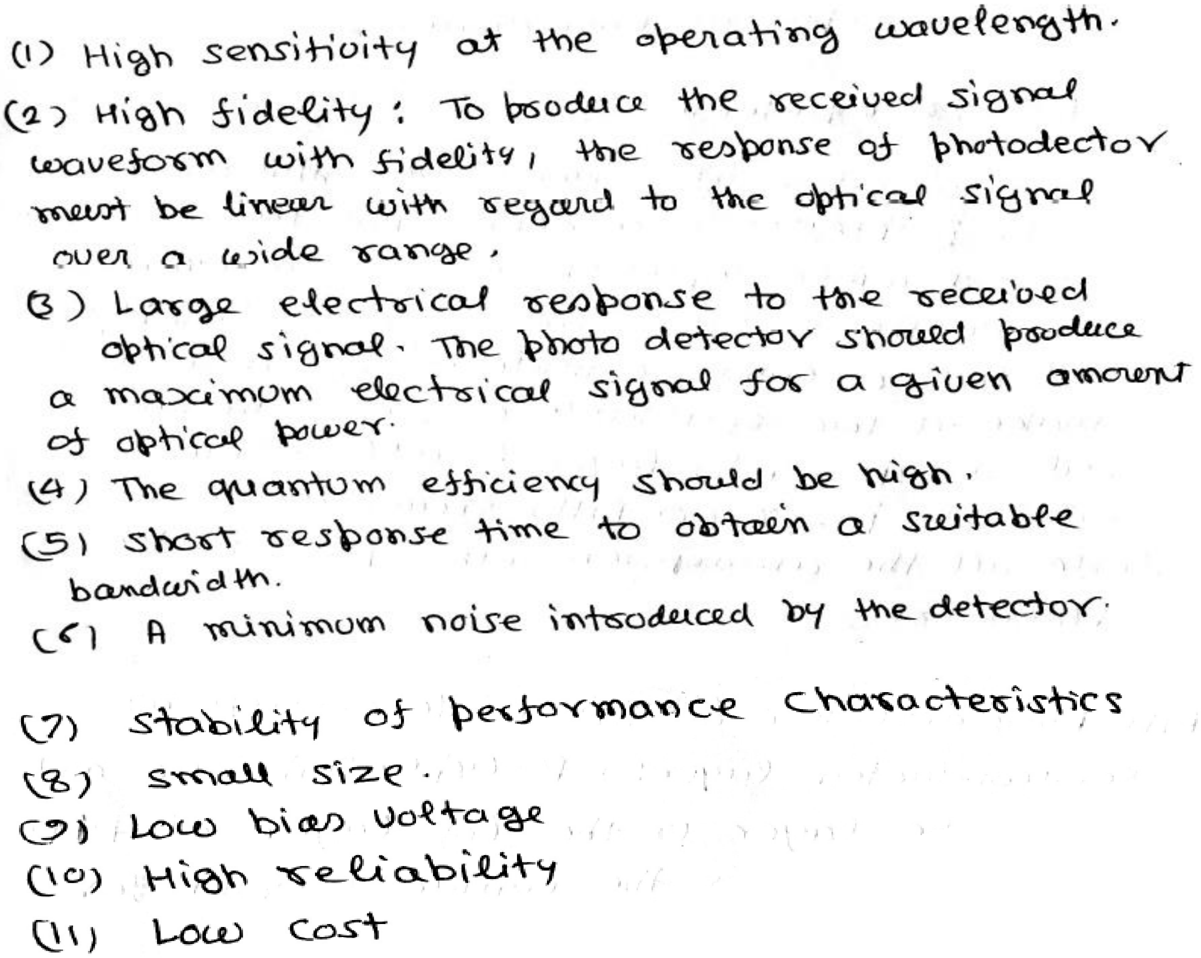
$$P_s = M B_o \lambda^2 \quad \text{———} (2)$$

* From equation ① and ② it is clear that two identically sized source operating at different wavelength but having identical radiances will launch equal amount of optical power into the same fiber.

Q2. Discuss the requirements of an ideal photo detector; also explain the construction and working of avalanche photodiode. [AKTU: 2021-22]

Photo Detectors -

The function of photo-detector is to convert the received optical signal into an electrical signal, which is then amplified before further processing. the requirements of an ideal photo-detector are given below -


(1) High sensitivity at the operating wavelength.

(2) High fidelity: To produce the received signal waveform with fidelity, the response of photodector must be linear with regard to the optical signal over a wide range.

(3) Large electrical response to the received optical signal. The photo detector should produce a maximum electrical signal for a given amount of optical power.

(4) The quantum efficiency should be high.

(5) short response time to obtain a suitable bandwidth.

(6) A minimum noise introduced by the detector.

(7) Stability of performance characteristics

(8) small size.

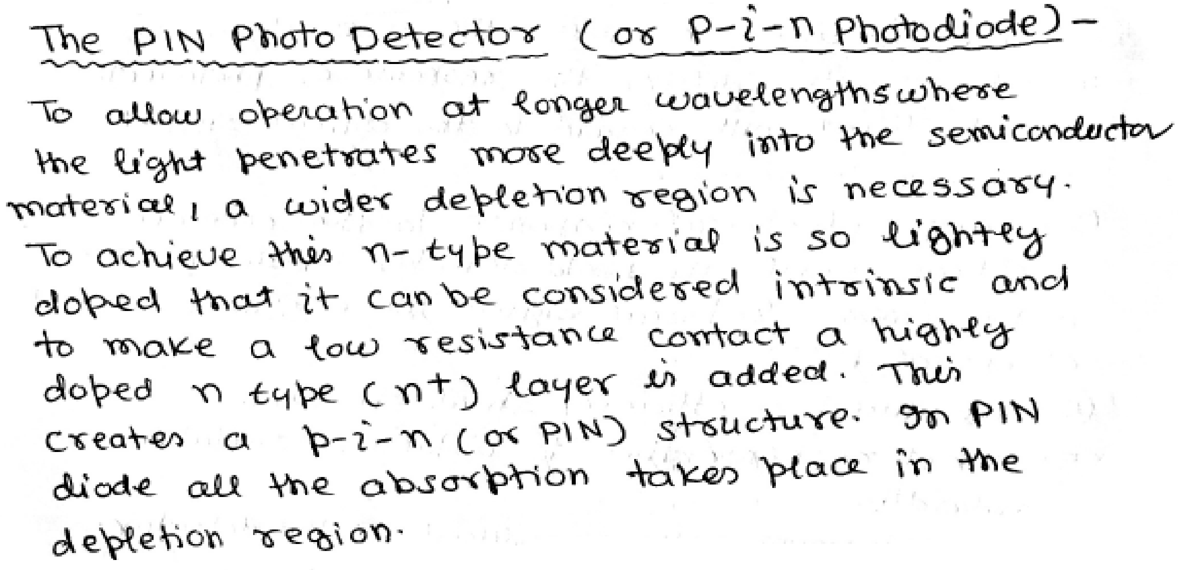
(9) Low bias voltage

(10) High reliability

(11) Low cost

Q3. Explain principle, construction and working of p-i-n diode. Discuss the factors which limit the speed of response of a photodiode. [AKTU: 2021-22, 2023-24]

ANS:

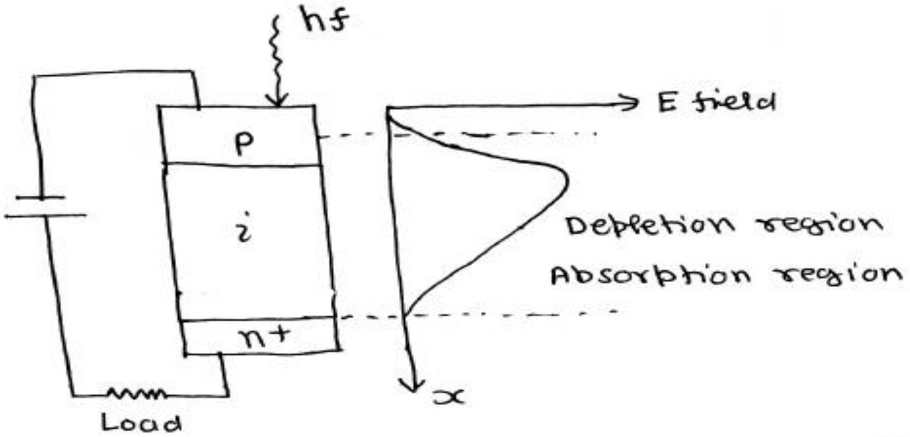

The PIN Photo Detector (or p-i-n Photodiode) -

To allow operation at longer wavelengths where the light penetrates more deeply into the semiconductor material, a wider depletion region is necessary. To achieve this n-type material is so lightly doped that it can be considered intrinsic and to make a low resistance contact a highly doped n type (n^+) layer is added. This creates a p-i-n (or PIN) structure. In PIN diode all the absorption takes place in the depletion region.

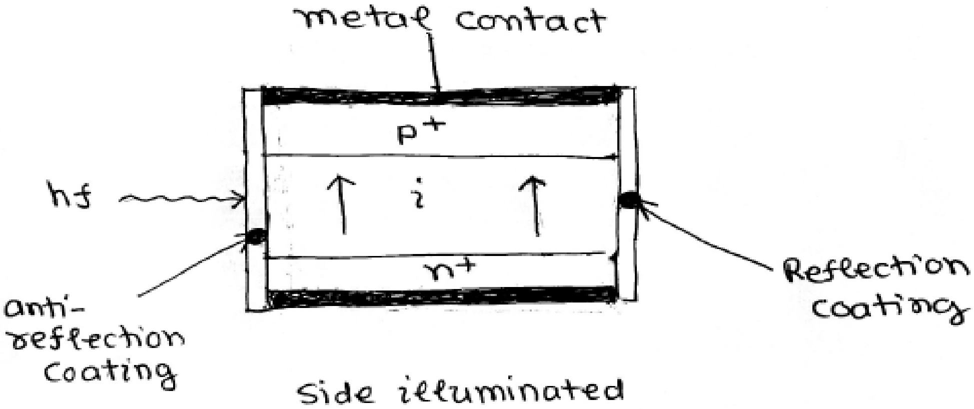
* A PIN Photodetector or PIN diode consists of three semiconductor layers, P-type, Intrinsic and N type. P-type layer is the top layer of PIN diode which serves as the contact region for incoming photons.

* The middle layer is the intrinsic (I) layer and it is undoped. This layer provides a region for the absorption of photons. when photons with sufficient energy strike this layer, they create electron-hole pairs.

* The bottom layer is n-type layer which acts as a collection region for generated electrons.



The P-i-N Photodiode showing the combined absorption and depletion.



Side illuminated P-i-n diode

* when photons of sufficient energy strikes the intrinsic layer, they generates electron-hole pairs. The electrons and holes are seperated by the electric field created between p and n^+ layers. Electrons move towards the N type layer and holes move toward P-type layer. The flow of these charge carriers create a photo current, which depends on the intensity of the incident light.

Factors Limit the speed of Response of a Photo-diode

The main factors that limit the speed of response of a photo diode are-

① Drift time of carriers through the depletion region - The speed of response of a photodiode is limited by the time it takes photo-generated carriers to drift across the depletion region.

$$t_{drift} = \frac{\omega}{\upsilon_d}$$

ω = width of the deplection layer

υ_d = drift velocity

② Diffusion time of carriers generated outside the depletion region - carrier diffusion is a comperatively slow process where the time taken t_{diff}, for carrier to diffuse a distance d may written as,

$$t_{diff} = \frac{d^2}{2D_c}$$

where D_c = minority carrier diffusion coefficient.

③ Time constant due to the capacitance of the photodiode with its load — A reverse biased photo diode exhibits a voltage-dependent capacitance caused by the variation in the stored charge at the junction. The junction capacitance Cj is given as,

$$C_j = \frac{\epsilon_s A}{\omega}$$

A = diode junction area
ω = width of depletion region
ϵ_s = Permitivity of semiconductor material

* Although all above factors affect the response time of the photodiode, the ultimate bandwidth of the device is limited by the drift time of carriers through the depletion region.

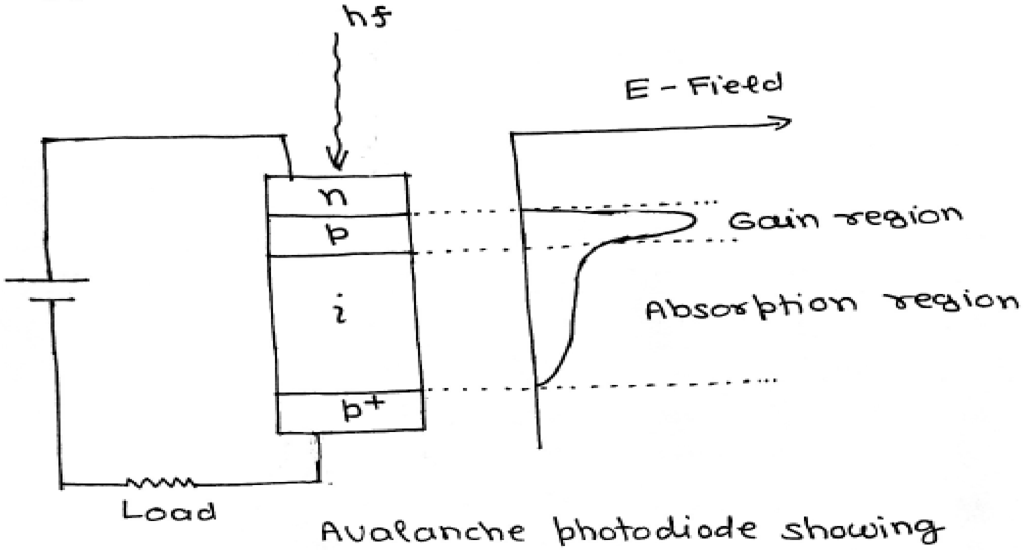
* Assuming no carriers are generated outside the depletion region and there is negligible junction capacitance, the maximum 3 dB bandwidth of the photodiode is given by—

$$B_m = \frac{1}{2\pi t_{drift}} = \frac{v_d}{2\pi\omega}$$

Q4. Explain the construction and working of APD photo diode. **[AKTU; 2023-24]**

ANS:

Avalanche Photodiode (APD)



Avalanche photodiode showing high electric field region

* An avalanche photodiode (APD) is a highly sensitive semiconductor detector that uses the photo-electric effect to convert optical signal into electrical signal. It has more sophisticated structure than p-i-n photodiode in order to create an extremely high electric field region (approximately 3×10^5 V/cm). Therefore as well as the deplection region where most of the photon are absorbed and electron-hole pairs are generated, there is a high field region in which holes and electrons can acquire sufficient energy to excite new electron-hole pairs. This process is known as impact ionization. It requires high reverse bias voltage (50 to 400V) in order that the new carriers created by impact ionization can themselves produce additional carriers.

Q5. When $3x10_{11}$photons each with a wavelength of 0.85 µm are incident on a photodiode, on average 1.2 x 10_{11}electrons are collected at the terminals of the device. Determine the quantum efficiency and responsivity . [AKTU: 2022-23]

ANS:

$$\text{Quantum efficiency } \eta = \frac{\text{number of electrons collected}}{\text{number of incident photons}}$$

$$= \frac{1.2\times10^{11}}{3\times10^{11}} = 0.4$$

$$= 40\%$$

$$\text{Responsivity } R = \frac{\eta e \lambda}{hc}$$

$$= \frac{0.4\times1.6\times10^{-19}\times0.85\times10^{-6}}{6.62\times10^{-34}\times3\times10^{8}}$$

$$= 0.274 \text{ A/W}$$

Q6. A germanium *p–i–n* photodiode with active dimensions of 100 × 50µm has a quantum efficiency of 55% when operating at a wavelength of 1.3 µm. The measured dark current at this wavelength is 8 nA. Calculate the noise equivalent power and specific detectivity for the device. It may be assumed that dark current is the dominant noise source. [AKTU: 2022-23]

ANS:

$$\eta = 0.55$$

$$\text{area } A = 100\times 0 \times 50\times10^{-6}$$

$$\lambda = 1.3\,\mu m = 1.3\times10^{-6}\,m$$

$$\text{dark current } I_d = 8\,nA = 8\times10^{-9}\,A$$

Noise equivalent Power

$$NEP = \frac{hc(2eI_d)^{1/2}}{\eta e \lambda}$$

$$NEP = \frac{hc(2eI_d)^{1/2}}{\eta e \lambda}$$

$$= \frac{6.62\times10^{-34}\times3\times10^{8}\times\left[2\times1.6\times10^{-19}\times8\times10^{-9}\right]^{1/2}}{0.55\times1.6\times10^{-19}\times1.3\times10^{-6}}$$

$$NEP \doteq 8.78\times10^{-14}\,W$$

$$\text{specific Detectivity } D = \frac{A^{1/2}}{NEP}$$

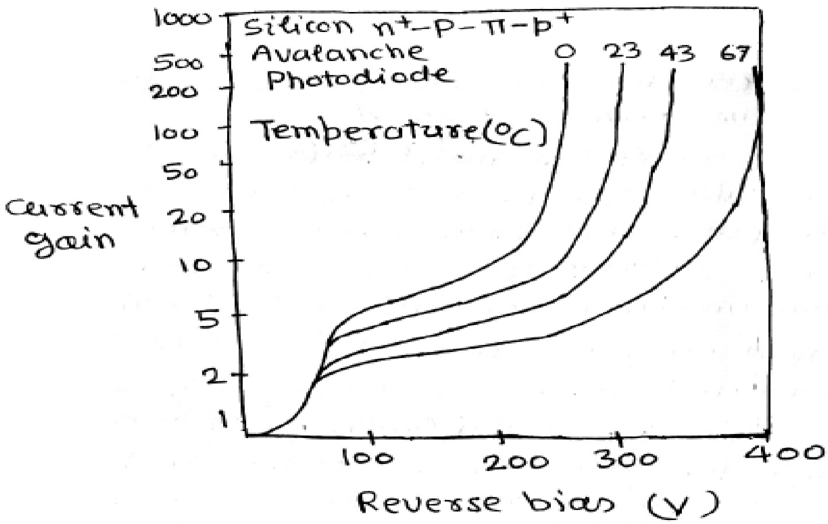
$$D = \frac{\left[100\times10^{-6}\times50\times10^{-6}\right]^{1/2}}{8.78\times10^{-14}} = 8.1\times10^{8}\,m\,Hz^{1/2}\,W^{-1}$$

Q7. Discuss the effect of temperature on avalanche gain.

ANS:

Temperature Effect on Avalanche Gain-

- * The gain of an avalanche photodiode is very sensitive to temperature because electron and hole ionization rates depends on temperature.
- * This temperature dependence is particularly critical at high bias voltage, where small changes in temperature can cause large variations in gain.



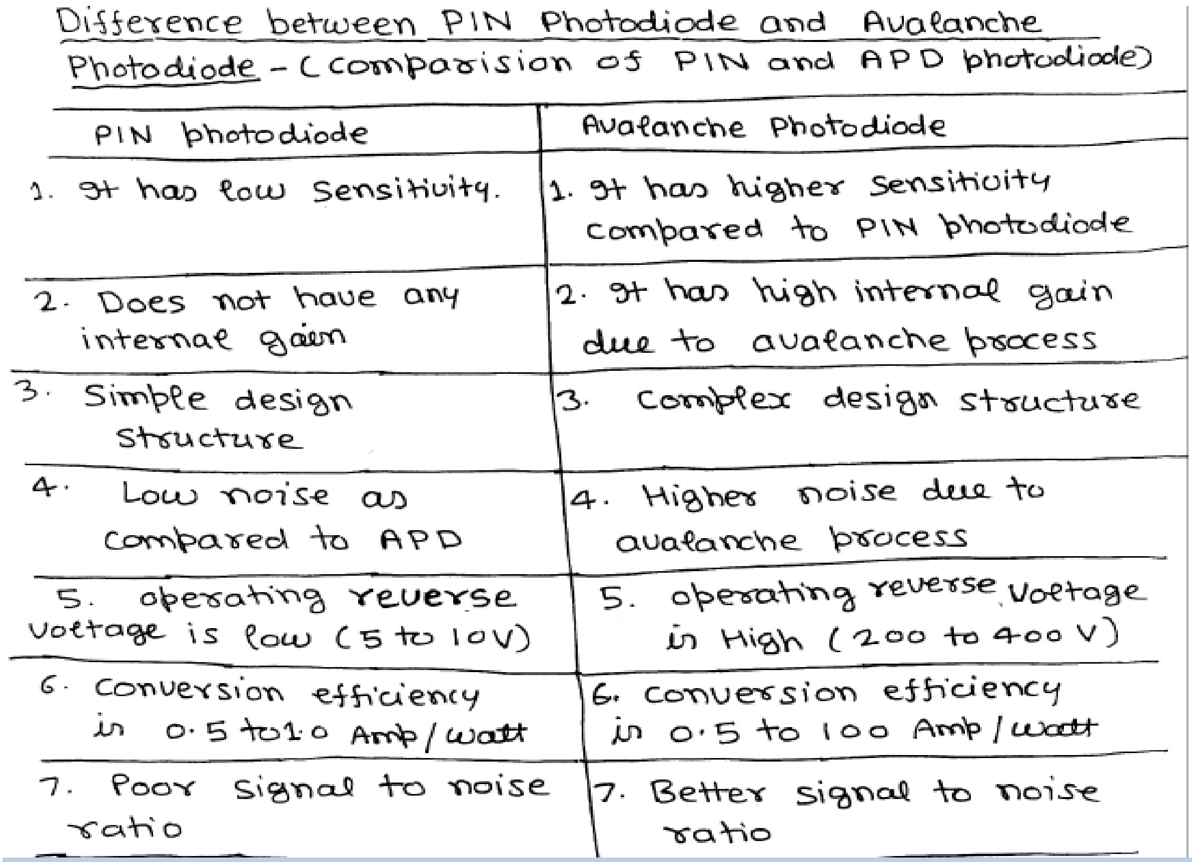
* above graph shows the variation of current gain (avalanche gain) with reverse voltage at different operating temperature for silicon photodiode.

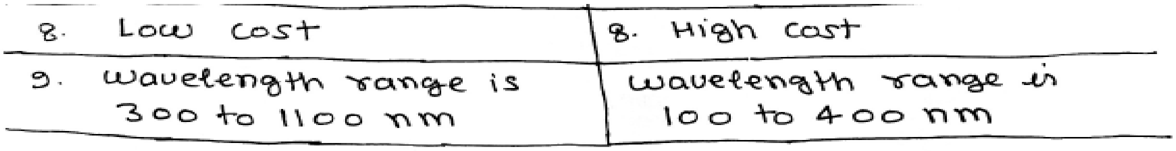
* As shown in graph, if the operating temperature decreases and applied bias voltage is kept constant, the ionization rates for electrons and holes will increase and hence avalanche gain will increase.

* So, to maintain constant gain as the temperature changes, the electric field in the multiplying region of the p-n junction must also be changed. So the photodetector uses a compensation circuit which adjusts the applied bias voltage on the photodetector when the temperature changes.

Q8. What are the difference between PIN photodiode and avalanche photodiode?

ANS:





Difference between PIN Photodiode and Avalanche Photodiode - (comparision of PIN and APD photodiode)

PIN photodiode	Avalanche Photodiode
1. It has low sensitivity.	1. It has higher sensitivity compared to PIN photodiode
2. Does not have any internal gain	2. It has high internal gain due to avalanche process
3. Simple design structure	3. Complex design structure
4. Low noise as compared to APD	4. Higher noise due to avalanche process
5. operating reverse voltage is low (5 to 10V)	5. operating reverse voltage in High (200 to 400 V)
6. conversion efficiency in 0.5 to 1.0 Amp/watt	6. conversion efficiency in 0.5 to 100 Amp/watt
7. Poor signal to noise ratio	7. Better signal to noise ratio
8. Low cost	8. High cost
9. wavelength range is 300 to 1100 nm	wavelength range in 100 to 400 nm

Q9. Explain the possible noise sources in a photodiode. Also explain quantum noise in detail.

[AKTU:2021-22]

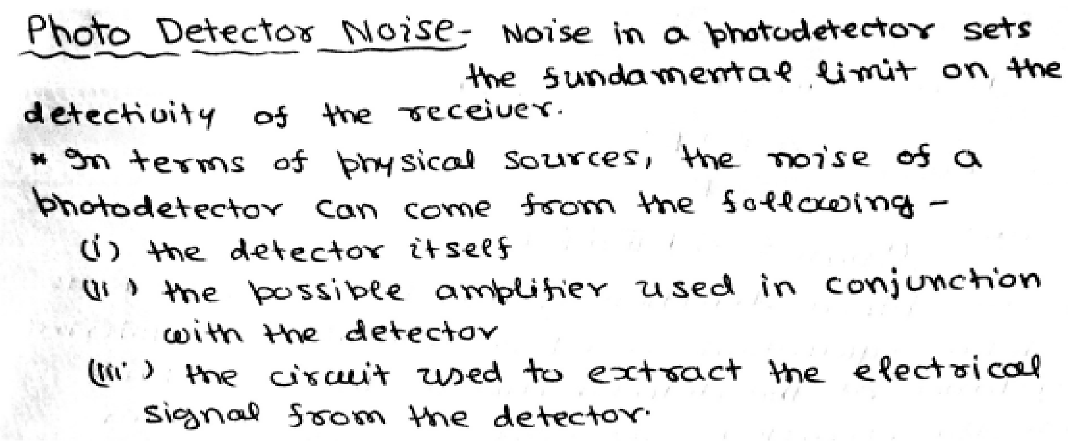


Photo Detector Noise- Noise in a photodetector sets the fundamental limit on the detectivity of the receiver.

* In terms of physical sources, the noise of a photodetector can come from the following -

(i) the detector itself
(ii) the possible amplifier used in conjunction with the detector
(iii) the circuit used to extract the electrical signal from the detector.

Quantum Noise / Shot noise - Discrete nature of electrons cause a signal disturbance called quantum noise or shot noise. It arises from the statistical nature of the production and collection of photo electrons. It is given by

$$i_S^2 = 2eBI_P$$

where I_P = photo current

B = Bandwidth of the received optical signal

Thermal Noise - Thermal noise results from the random thermal motion of the electrons in a conductor. The total thermal noise power for a detection system of a bandwidth B is given by

$$P_{n,th} = 4KTB$$

where T = Temperature

K = Boltzmann's constant

For a resistor that has a resistance R,

$$P_{n,th} = \overline{i^2_{n,th}} R = \overline{v^2_{n,th}} / R$$

$$\overline{i^2_{n,th}} = \frac{4KTB}{R}$$

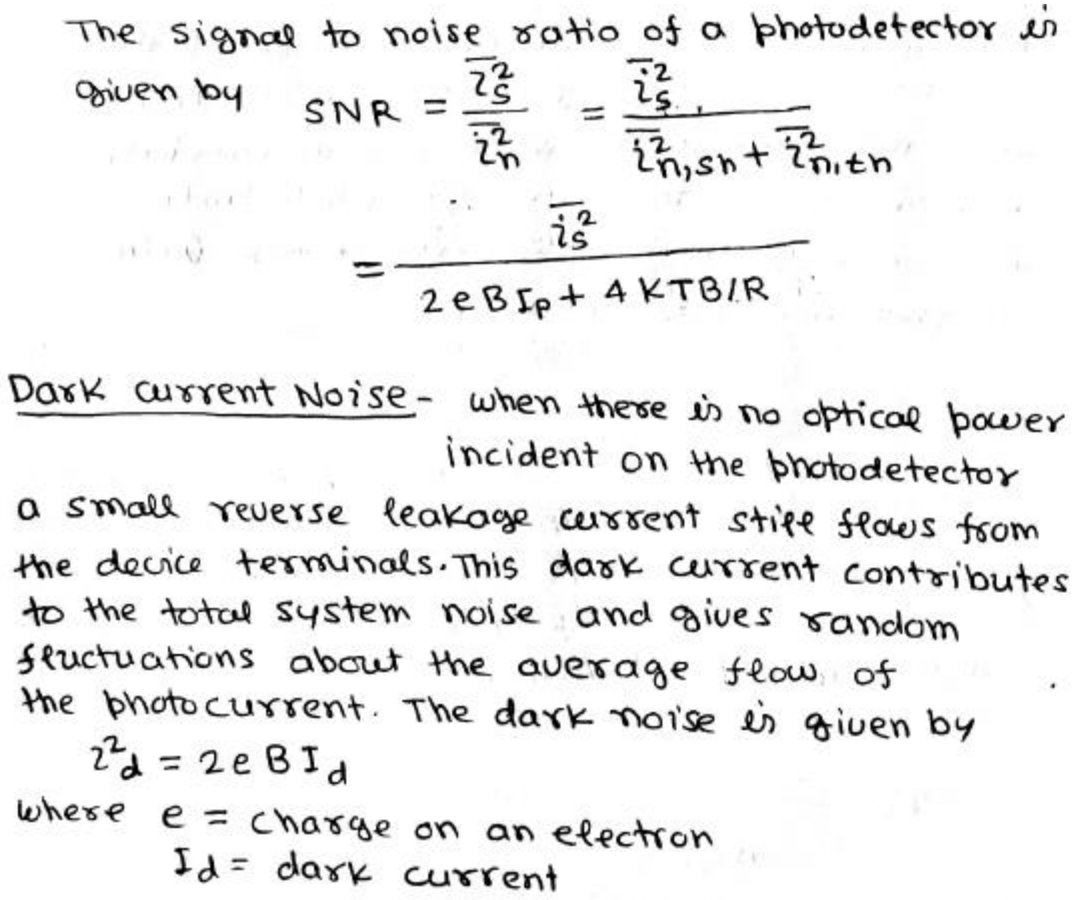
and, $\overline{v^2_{n,th}} = 4KTBR$

For an optical detection system, the resistance R is the total equivalent resistance including the internal resistance of the detector and the load resistance from the circuit at the output of the detector.

Signal to noise Ratio -

The total noise of a photodetector is the sum of its shot noise and thermal noise.

$$\overline{i_n^2} = \overline{i^2_{n,sh}} + \overline{i^2_{n,th}}$$



The signal to noise ratio of a photodetector is given by

$$SNR = \frac{\overline{i_s^2}}{\overline{i_n^2}} = \frac{\overline{i_s^2}}{\overline{i_{n,sh}^2} + \overline{i_{n,th}^2}}$$

$$= \frac{\overline{i_s^2}}{2eBI_p + 4KTB/R}$$

Dark current Noise - when there is no optical power incident on the photodetector a small reverse leakage current still flows from the device terminals. This dark current contributes to the total system noise and gives random fluctuations about the average flow of the photocurrent. The dark noise is given by

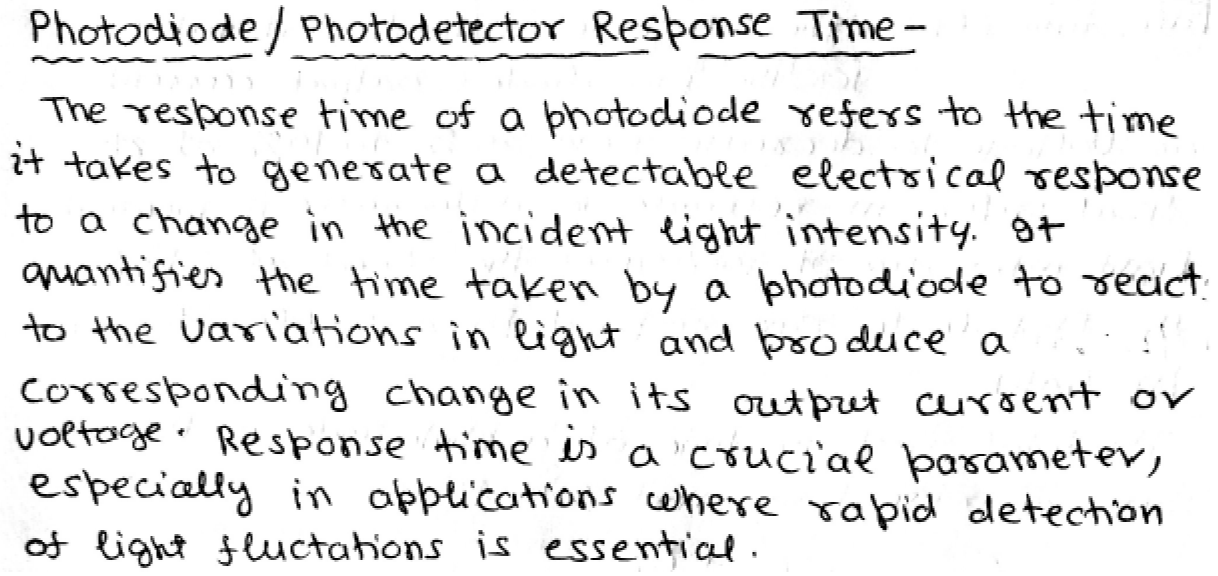
$$i^2_d = 2eBI_d$$

where e = charge on an electron

I_d = dark current

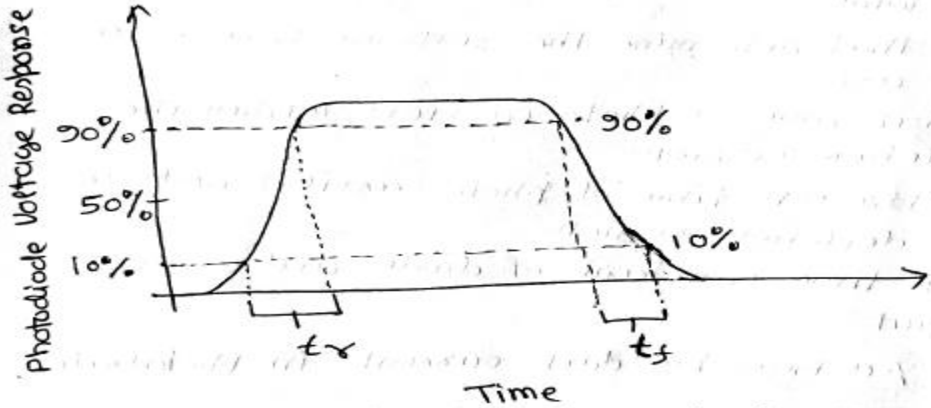
Q10. Discuss photo detector response time in detail.

ANS:



Photodiode / Photodetector Response Time -

The response time of a photodiode refers to the time it takes to generate a detectable electrical response to a change in the incident light intensity. It quantifies the time taken by a photodiode to react to the variations in light and produce a corresponding change in its output current or voltage. Response time is a crucial parameter, especially in applications where rapid detection of light fluctations is essential.



There are two primary components that make up the response time of a photodiode.

(1) Rise time (t_r)
(2) Fall time (t_f)

Rise Time (t_r) - The rise time is the time it takes for the photodiode's output current or voltage to increase from 10% to 90% of its final value in response to an increase in the incident light intensity. It measures the speed at which the photodiode can response to a sudden increase in light.

Fall Time (t_f) - The fall time is the time it takes for the photodiode's output current or voltage to decrease from 90% to 10% of its final value in response to a decrease in incident light intensity. It measures the speed at which the photodiode can respond to a sudden decrease in light.

The total response time of a photodiode is the sum of rise time and fall time.

$$t_{Total} = t_r + t_f$$

* The factors that determine the response time of a photodiode are-
    - (i) transit time of photo carriers within the depletion region.
    - (ii) Duffusion time of photo carriers outside the depletion region.
    - (iii) RC time constant of diode and external circuit.