(MPM-202)
Optoelectronics and Optical Communication System

UNIT-II (Optical Sources and Detectors)

Lecture-8

by

Prof. D. K. Dwivedi
Physics and Material Science Department
Madan Mohan Malaviya University of Technology, Gorakhpur

SYLLABUS

MPC-202 OPTOELECTRONICS AND OPTICAL COMMUNICATION SYSTEM Credits 4 (3-1-0)

UNIT I: Optical process in semiconductors

Optoelectronic properties of semiconductor: effect of temperature and pressure on bandgap, carrier scattering phenomena, conductance processes in semiconductor, bulk and surface recombination phenomena, optical properties of semiconductor, EHP formation and recombination, absorption in semiconductors, effect of electric field on absorption.

UNIT II: Optical sources and detectors

An overview of optical sources (Semiconductor Laser and LEDs), Optical Detectors: Type of photo detectors, characteristics of photo detectors, noise in photo detectors, photo transistors and photo conductors.

UNIT III: Optical fiber

Structure of optical wave guide, light propagation in optical fiber, ray and wave theory, modes of optical fiber, step and graded index fibers, transmission characteristics of optical fibers, signal degradation in optical fibers; attenuation, dispersion and pulse broadening in different types of optical fibres.

UNIT IV: Fiber components and optoelectronic modulation

Fiber components: Fibre alignments and joint loss, fiber splices, fiber connectors, optical fiber communication, components of an optical fiber communication system, modulation formats, digital and analog optical communication systems, analysis and performance of optical receivers, optoelectronic modulation.

Photodetector Requirements

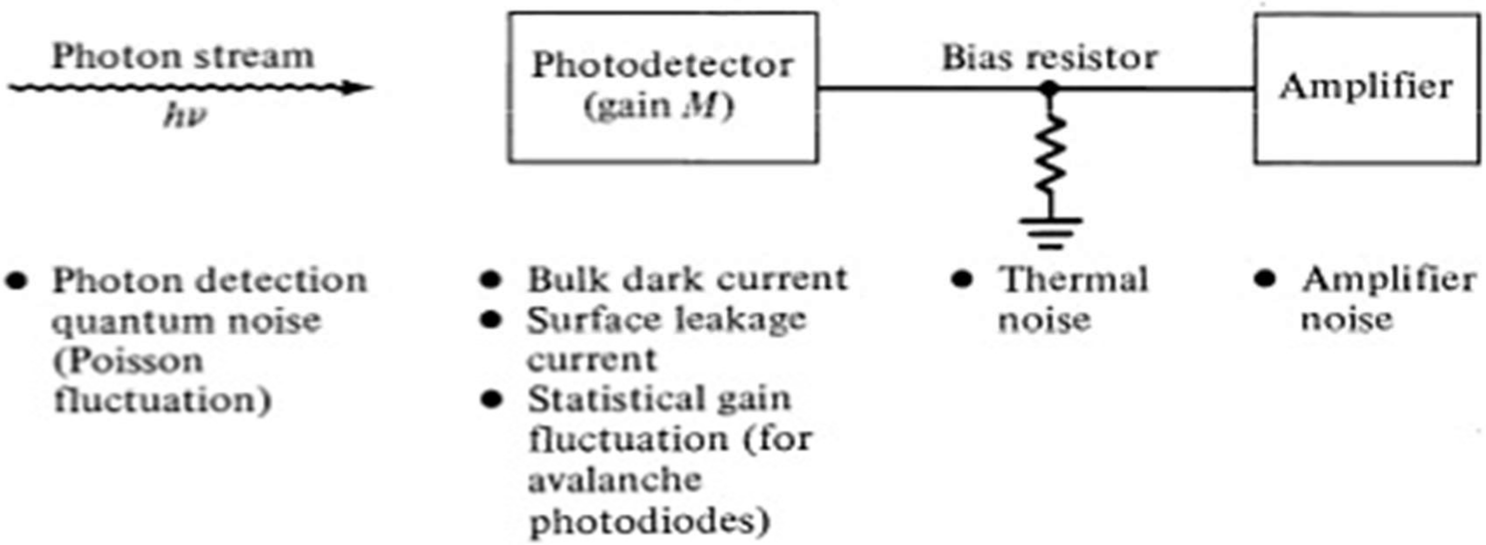
- Good sensitivity (responsivity) at the desired wavelength and poor responsivity elsewhere i.e. wavelength selectivity
- Fast response time
- Compatible physical dimensions
- Low noise
- Insensitive to temperature variations
- Long operating life and reasonable cost.

Noise in Photodetectors

- In the fiber communication systems, the photodiode is generally required to detect very weak optical signals.
- Detection of weak optical signals requires that the photodetector and its amplification circuitry be optimized to maintain a given signal-to-noise ratio.
- The power signal to noise ratio S/N (also designated by SNR) at the output of an optical receiver is defined by

$$SNR = \frac{S}{N} = \frac{signal\ power\ from\ photocurrent}{photodetector\ noise\ power + amplifier\ noise\ power}$$

Noise sources and Disturbances



Photon noise – the most fundamental source of noise is associated with the *random* arrivals of the photons (usually described by *Poisson statistics*)

Photoelectron noise – a single photon generates an electron-hole pair with probability η. The photocarrier-generation process is random.

Gain noise – the amplification process that provides internal gain in certain photodetectors is stochastic.

Receiver circuit noise – various components in the electrical circuitry of an optical receiver, such as *thermal noise* in resistors.

Performance Measures

- The ***signal-to-noise ratio*** (SNR) of a random variable - the ratio of its *square-mean to its variance*. Thus, the SNR of the current i is SNR = $\langle i \rangle^2/\sigma_i^2$, while the SNR of the photon number is SNR = $\langle n \rangle^2/\sigma_n^2$

- The ***minimum-detectable signal*** – the *mean* signal that yields SNR = 1

- The ***bit error rate*** (BER) – the probability of error per bit in a digital optical receiver.

- The ***receiver sensitivity*** – the signal that corresponds to a prescribed value of the SNR. While the *minimum-detectable signal* corresponds to a *receiver sensitivity* that provides SNR = 1, a higher value of SNR is often specified to ensure a given value of accuracy
  (e.g. SNR = $10 - 10^3$ corresponding to 10 – 30 dB).
  For a digital system, the receiver sensitivity is defined as the *minimum optical energy or corresponding mean number of photons per bit* required to attain a prescribed BER (e.g. BER = 10^{-9} or better).

Photon Noise

- The photon flux associated with a fixed optical power P is inherently uncertain (statistical).

- The mean photon flux is $\Phi = P/h\upsilon$, but this quantity fluctuates randomly in accordance with a probability law that depends on the nature of the light source.

- The number of photons n counted in a time interval T is thus random with *mean* $\langle n \rangle = \Phi T$.

- For *monochromatic coherent* radiation, the photon number statistics obeys the *Poisson probability distribution* $\sigma_n^2 = \langle n \rangle$ (i.e. variance equals mean)

=> the fluctuations associated with an *average of 100* photons result in an actual number of photons that lies approximately within the range 100 ± 10.

Photon-number signal-to-noise ratio

- The *photon-number signal-to-noise ratio*

$$SNR = \langle n \rangle^2 / \sigma_n^2 = \langle n \rangle$$

  and the *minimum-detectable photon number*

$$\langle n \rangle = 1 \text{ photon}$$

- If the observation time $T = 1\ \mu s$ and the wavelength $\lambda = 1.24\ \mu m$, this is equivalent to a *minimum detectable power* of 0.16 pW. ($e = 1.6 \times 10^{-19}$ C)

- The *receiver sensitivity* for $SNR = 10^3$ (30 dB) is 1000 photons. If the time interval $T = 10$ ns, this is equivalent to a sensitivity of 10^{11} photons/s or an optical power sensitivity of 16 nW at $\lambda = 1.24\ \mu m$.

Photoelectron Noise

- A photon incident on a photodetector of quantum efficiency η generates an electron-hole pair or liberates a photoelectron with probability η.
- An incident mean photon flux Φ (photons/s) therefore results in a *mean photoelectron flux* $\eta\Phi$.
- The number of photoelectrons m detected in the time interval T is a random variable with mean

$$\langle m \rangle = \eta\, \Phi T = \eta\, \langle n \rangle$$

- If the photon number follows the *Poisson probability distribution*, so is the photoelectron number.
- => the photoelectron-number variance $\sigma_m^2 = \langle m \rangle = \eta\, \langle n \rangle$

Photoelectron Noise

- ***Photoelectron-number signal-to-noise ratio***

$$\mathrm{SNR} = \langle m \rangle = \eta \langle n \rangle$$

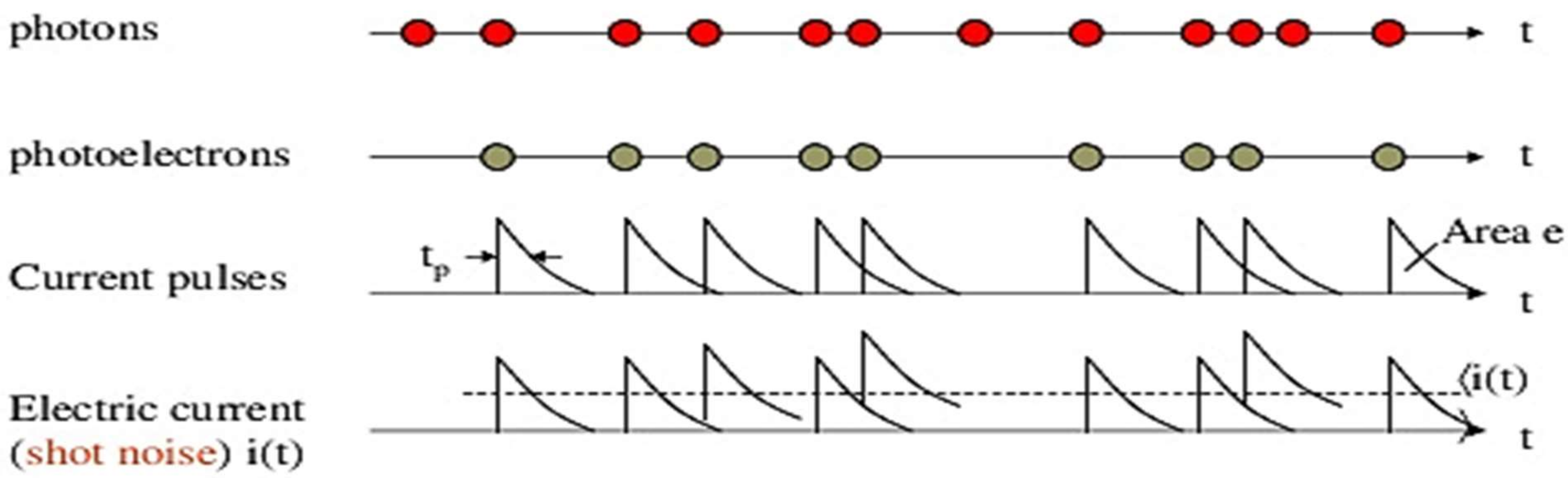
- The *minimum-detectable photoelectron number* is $\langle m \rangle = \eta \langle n \rangle = 1$ photoelectron, corresponding to $1/\eta$ photons (i.e. > 1 photons).
- The *receiver sensitivity* for $\mathrm{SNR} = 10^3$ is 1000 photoelectrons or $1000/\eta$ photons.

Photocurrent Noise

- Here we examine the properties of the electric current i(t) induced in a circuit by a random photoelectron flux with mean $\eta\Phi$.
- We include the effects of *photon noise*, photoelectron *noise*, and the *characteristic time response of the detector and circuitry* (*filtering*).
- Assume every photoelectron-hole pair generates a pulse of electric current with charge (*area*) *e* and time duration τ_p in the external circuit of the photodetector.
- A photon stream incident on a photodetector therefore results in a stream of current pulses which add together to constitute the photocurrent i(t).

  => The randomness of the photon stream is transformed into a fluctuating electric current. *If the incident photons are Poisson distributed*, these fluctuations are known as ***shot noise***.

Shot Noise



- The photocurrent induced in a photodetector circuit comprises a *superposition of current pulses*, each associated with a detected photon. The individual pulses illustrated are exponentially decaying step functions but they can assume an arbitrary shape.

Shot Noise

- Consider a photon flux Φ incident on a photoelectric detector of quantum efficiency η.
- Let the random number m of photoelectrons counted within a *characteristic time interval* $T = 1/2B$ (the resolution time of the circuit) generate a photocurrent i(t), where t is the instant of time immediately following the interval T. (*The parameter B represents the bandwidth of the device/circuit system.*)
- For *rectangular* current pulses of duration T, the current and photoelectron-number random variables are related by $i = (e/T)\, m$.
- The *photocurrent mean* and *variance* are

$$\langle i \rangle = (e/T)\, \langle m \rangle$$

$$\sigma_i^2 = (e/T)^2\, \sigma_m^2$$

where $\langle m \rangle = \eta\Phi T = \eta\Phi/2B$ is the *mean number of photoelectrons collected* in the time interval $T = 1/2B$.

Shot Noise

- Substituting $\sigma_m{}^2 = \langle m \rangle$ for the *Poisson* law yields the *photocurrent mean* and *variance*

$$\langle i \rangle = e\eta\Phi$$
$$\sigma_i{}^2 = 2e\,B\,\langle i \rangle$$

- => the *photocurrent SNR*

$$\mathrm{SNR} = \langle i \rangle^2/\sigma_i{}^2 = \langle i \rangle/2eB = \eta\Phi/2B = \langle m \rangle$$

- The current SNR is *directly proportional to the photon flux Φ* and *inversely proportional to the electrical bandwidth of the circuit B*.
- *The result is identical to that of the photoelectron-number SNR ratio* $\langle m \rangle$ as expected as the circuit introduces no added randomness.

Dark Current Noise

- *When there is no optical power* incident on the photodetector a *small reverse leakage current* still flows from the device terminals.
- Dark-current noise results from random electron-hole pairs generated *thermally* (or by tunneling).
- This dark current contributes to the *total system noise* and *gives random fluctuations about the average photocurrent*.

  => *It therefore manifests itself as* *shot noise* on the photocurrent.

- The ***dark current noise*** is

$$\sigma_d^2 = 2\, eB \langle I_d \rangle$$

Thermal Noise

- Thermal noise (also called *Johnson noise* or *Nyquist noise*) results from *random thermal motions of the electrons in a conductor*. It is associated with the *blackbody radiation of a conductor* at the radio or microwave frequency range of the signal.
- Because *only materials that can absorb and dissipate energy* can emit blackbody radiation, thermal noise is generated *only by the resistive components* of the detector and its circuit. (*Capacitive and inductive components do not generate thermal noise because they neither dissipate nor emit energy.*)
- These motions give rise to a *random electric current even in the absence of an external electrical power source*. The thermal electric current in a resistance R is a random function i(t) whose mean value $\langle i(t) \rangle = 0$.

=> the variance of the current $\sigma_i^2 = \langle I_{th}^2 \rangle$


THANK YOU