UNIT-IV

PHOTO DETECTORS –

PHYSICAL PRINCIPLES OF PHOTO DIODES,
PHOTO DETECTOR NOISE: SNR, DETECTOR
RESPONSE TIME, AVALANCHE
MULTIPLICATION NOISE, COMPARISONS OF
PHOTO DETECTORS.

FUNDAMENTAL RECEIVER OPERATION –

PREAMPLIFIERS,
ERROR SOURCES,

RECEIVER CONFIGURATION –

PROBABILITY ERROR,
QUANTUM LIMIT.

PHOTO DETECTORS:

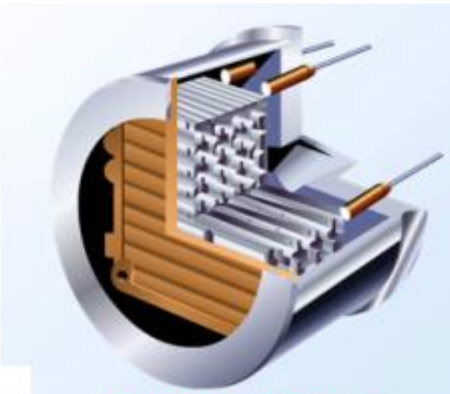
The Photo Detector senses the luminescent power falling and converts the variation of the optical power into a corresponding varying electric current. The Photo Detector must meet very high performance requirements those are with high response or sensitivity in the emission wavelength.

Photo Detectors

In OFC system there must be a receiving device which interprets the information contained in the optical signal. The first element of this receiver is a photodetector. Different types of photodetectors are in existence. They are Photo multipliers, Pyroelectric detectors, Photo diodes.

Photomultipliers: Photomultipliers consists of a photocathode and an electron multiplier packaged in a vaccum tube that are capable of providing very high gain and very low noise.

Pyroelectic Detectors: Pyroelectric photo detectors involve the conversion of photons to heat. They give rise to variation in the dielectric constant which is usually measured as a capacitance change.



Photomultipliers

Pyroelectric photo detector

Photodiode: Photodiode is used almost for all fiber optic systems because of its small size, suitable material, high sensitivity & fast response time.

Two types of photo diodes are (1) PIN photo detector (2) Avalanche Photo diode [APD]

THE PIN PHOTODETECTOR:

The most commonly used photo detector is the photodiode. The device structure consists of p & n regions separated by a very lightly n-doped intrinsic region. In normal operation a sufficiently large reverse bias voltage is applied across the device so that the intrinsic region is fully depleted of carriers. So, the intrinsic n-carrier and p-carrier concentration is negligibly small and it is compared with impurity concentration.

When an incident photon has energy greater than or equal to the band-gap energy, the photon can give up its energy and exit an electron from valance band to the conduction band.

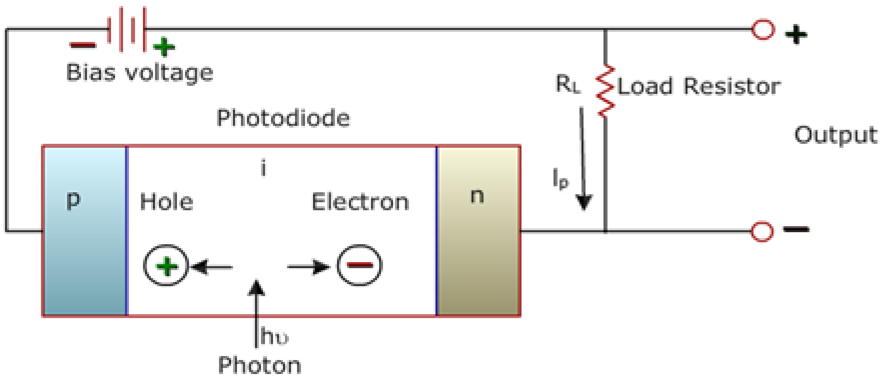
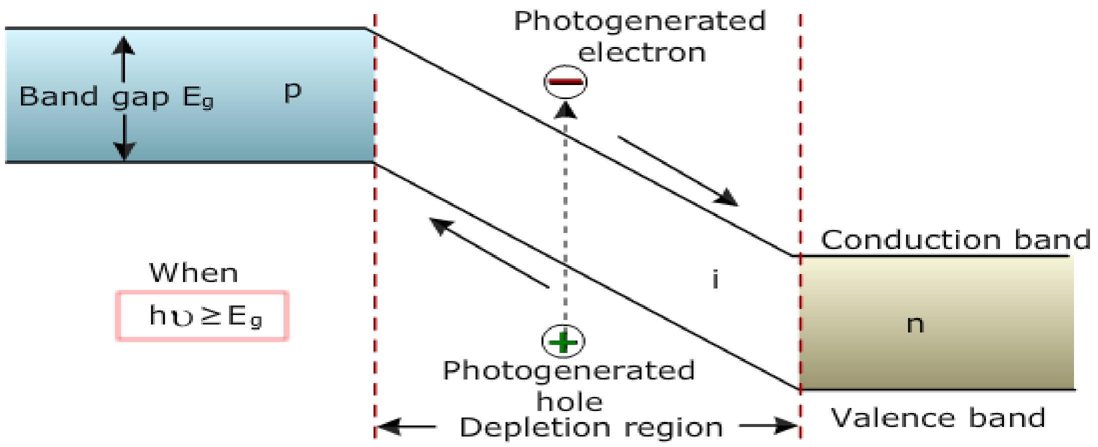


Figure 4.1: Schematic representation of a pin photodiode circuit with an applied reverse bias.



Energy Band Diagram for a Pin Photodiode

This process generates free electron-hole pairs which are known as photo carriers (or) Photon-generated charge carriers. The carriers are generated in depletion region where most of incident light is observed. The high electric field present in the depletion region causes the carrier to separate and collected across the reverse bias junction.

This gives a current flow in an external circuit, with electron flow for every carrier pair generated. This current flow is known as photo current. As the charge carrier flow through the material, some electron-hole will recombine & hence disappear.

The charge carrier travels at distance L_n or L_p for electrons and holes respectively. This distance is known as diffusion length. The time it takes for an electron or hole to recombination is known as carrier life time & is represented by T_n & T_p respectively.

Life times & diffusion lengths are related by

$$L_n = (D_n T_n)^{1/2} \ \& \ L_p = (D_p T_p)^{1/2}$$

where D_n & D_p are electron and hole diffusion coefficients.

The optical radiation is absorbed as $P(x) = P_o(1- e(-\alpha_s(\lambda)x))$ where $\alpha_s(\lambda)$ is absorption coefficient at a wavelength λ, Po = the incident optical power level P(x)=optical power absorbed in a distance x

If the depletion region has a width w, then the total power absorbed in the distance w is $P(w)=P_o(1- e(- \alpha_s w))$

The primary photocurrent $I_p= (q/hv)*P_o(1- e (- \alpha_s w))(1-R_f)$

Where P_o=optical power incident on Photodetector, q=electron charge,

R_f=refractivity, hv=photon energy

The quantum efficiency Ƞ is the no. of electron-hole carrier pairs generated per incident photon of energy hv is given by

Ƞ = no. of electron-hole pairs generated / no. of incident photons

$= [I_p/q] / [P_o/hv]$

where I_p=average photo current generated by a steady-state average optical power P_o incident on the photodetector.

Problem: In a 100ns pulse $6x10^{(6)}$ photons at a wavelength of 1300nm on an InGaAs photodetector. On the average $3.9x10^{(6)}$ electron hole pair is generated. The quantum efficiency is ---------

Ans. Ƞ$=3.9x10^6 / 6x10^6 = 0.65$

Thus the quantum efficiency at 1300nm is 65%.

AVALANCHE PHOTODIODES:

APDs internally multiply the primary signal before it enters the input circuitry of the following amplifier. In order for carrier multiplication to take place, the photo generated carriers must traverse a region where very high electric field is present. The carrier multiplication mechanism is known as impact ionization.

The newly created carriers are also accelerated with high electric field, thus gaining enough energy to cause further impact ionization. This phenomenon is called as Avalanche effect.

A commonly used structure for achieving carrier multiplication with the little excess noise is the reach through construction. RT photo diode is composed of high resistive p type material deposited as an epitaxial layer on a p+[heavily doped p-type] substrate.

A p-type diffusion or ion implant is then made in the high-resistive material followed by construction of an n^+[heavily doped] layer. This configuration is referred to as a $p^+\Pi pn^+$ reach through structure.

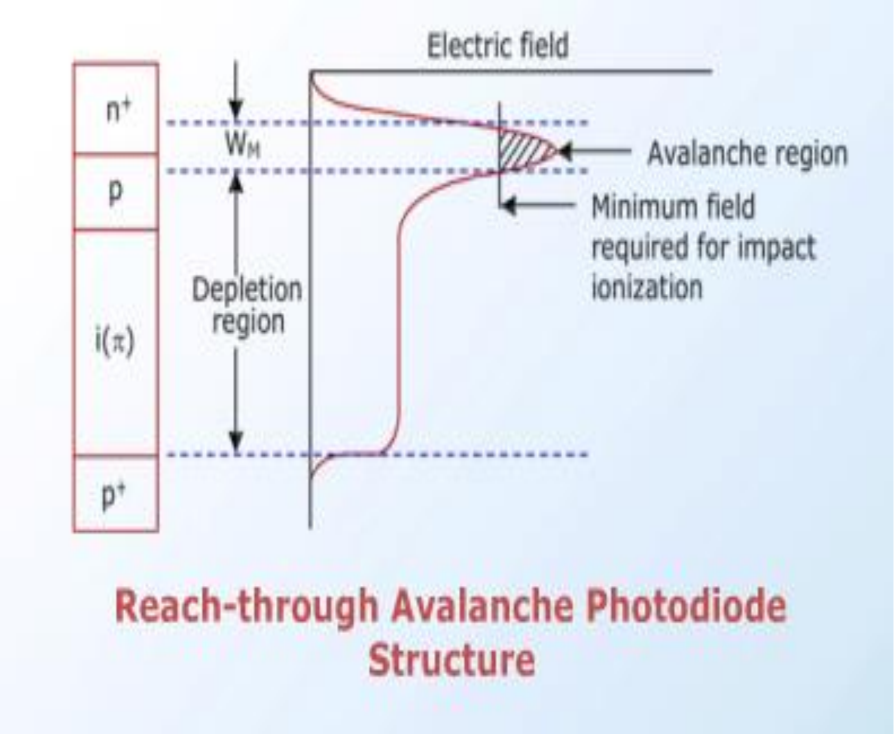


Figure 4.2: Reach-through avalanche photodiode structure and electric fields in the depletion and multiplication regions.

The Π layer is basically an intrinsic material. In normal usage RAPD is operated in the fully depleted mode. Light enters the device through p+ region and is absorbed in Π material, which acts as the collection region for photo generated carriers.

The average no. of electron hole pairs created by a carrier per unit distance traveled is called the ionization rate. The multiplication M for all carriers generated in the photodiode is

$M=I_m/I_p$ where I_m= average value of the total multiplied output current.
I_p= the primary unmultiplied photo current.

PHOTODETECTOR NOISE & SNR:

In fiber optic communication systems the photodiode is generally required to detect very weak optical signals. Detection of the weakest possible optical signals requires that the photodetector and its following amplification circuit to optimize so that a given SNR is maintained.

The SNR at the output of an optical receiver is defined by

$$[S/N] = \frac{\text{signal power from photocurrent}}{\text{photodetector noise power + amplifier noise power}} \quad \text{------ [1]}$$

To achieve a high SNR, the following conditions should met:

- The photodetector must have a high quantum efficiency to generate a large signal power.
- The photodetector and amplifier noises should be kept as low as possible. The sensitivity of a photodetector in an optical fiber communication system is describable in terms of the minimum detectable optical power. This is optical power necessary to produce a photocurrent of the same magnitude as the root mean square of the total noise current.

The interrelationship of the different types of noises affecting the SNR, consider a simple receiver model and its equivalent circuit shown in figure 4-2. The photo diode has small series resistance R_S, total capacitance C_d consisting of junction and packaging capacitances, and bias (or load) resistor R_L. The amplifier following the photodiode has an input capacitance C_d & a resistance R_a. For practical purposes, R_S is much smaller than the load resistance R_L and can be neglected.

If a modulated signal of optical power P(t) falls on the detector, the primary photo current $i_{ph}(t)$ generated is

$$i_{ph}(t) = \frac{\eta q}{h\nu} P(t) \quad \text{-------- (2)}$$

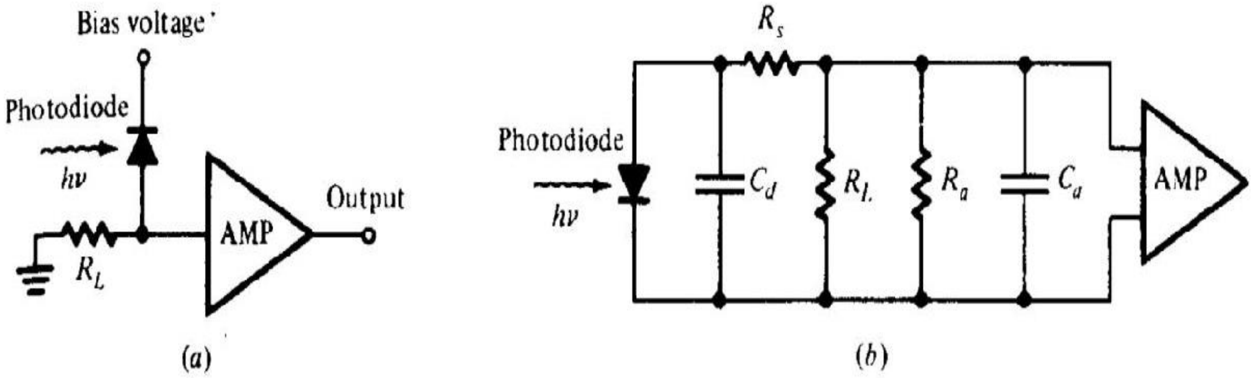


Figure 4.3: (a) simple model of a photodetector receiver (b) its equivalent circuit.

This primary current consists of a dc value Ip, which is the average photocurrent due to the signal power and a signal component $i_p[t]$. For pin photodiodes the mean square signal current $< i_s^2>$ is

$< i_s^2> = < i_p^2[t]> \rightarrow$ [3a]

Whereas for avalanche photodetectors, $< i_s^2>$ is

$< i_s^2> = < i_p^2[t]>M^2 \rightarrow$ [3b]

where M is the average of the statistically varying avalanche gain.

For a sinusoidal varying input signal of modulation index m, the signal component $< i_p^2>$ is of the form

$< i_p^2[t]> = [m^2/2]I_p^2 \rightarrow$[4] where m is modulation index.

The principal noises associated with quantum noise, dark-current noise generated in the bulk material of the photodiode and surface leakage current noise.

The quantum or shot noise arises from the statistical nature of the production and collection of photoelectrons when an optical signal is incident on a photodetector. The quantum noise current has a mean square value in a bandwidth B which is proportional to the average value of the photocurrent Ip

$<iQ^2> = 2qI_pBM^2F(M) \rightarrow$[5]

where F(M) is a noise figure associated with the random nature of the avalanche process.

The photodiode dark current is the current that continues to flow through the bias circuit of the device when no light is incident on the photodiode. This is the combination of bulk and surface currents. The bulk dark current i_{DB} arises from the electrons or holes which are thermally generated in the pn junction of the photodiode. The mean square value of this current is given by

$<i_{DB}^2> = 2qI_DM^2F(M)B \rightarrow$[6]

where I_D is the primary detector bulk current.

The surface dark current is also referred to as a surface leakage current of simply the leakage current. It is dependent on surface defects, cleanliness, bias voltage & surface area. The mean square value of the surface dark current is given by

$$\langle i_{DS}^2 \rangle = 2qI_L B \rightarrow [7]$$

Since the dark currents and the signal current are uncorrelated, the total mean square photodetector noise current

$$\langle i_N^2 \rangle = \langle i_Q^2 \rangle + \langle i_{DB}^2 \rangle + \langle i_{DS}^2 \rangle$$
$$= 2q(I_p + I_D)M^2F(M)B + 2qI_L B \rightarrow [8]$$

The photodetector load resistor contributes a mean square (Johnson) thermal noise current

$$\langle i_T^2 \rangle = [4K_B TB]/R_L \rightarrow [9]$$

where K_B is Boltzmann's constant and T is the absolute temperature.

$$\frac{S}{N} = \frac{\langle i_p^2 \rangle M^2}{2q(I_p+I_D)M^2F(M)B + 2qI_L B + 4K_B TB/R_L} \rightarrow [10]$$

DETECTOR RESPONSE TIME:

The response time of photo diode together with its output circuit depends mainly on the allowing 3 factors:

[a] The transit time of the photo carrier in the depletion region.
[b] The diffusion time of the photo carriers generated outside the depletion region.
[c] The RC time constant of the photodiode and its associated circuit.

Photo diode parameters responsible for these 3 factors are absorption coefficient α_s, depletion region width w, photodiode junction & package capacitance, the amplifier capacitance, the detector load resistance, the amplifier input resistance and photo diode series resistance.

Transit time of photocarriers in the depletion region:

The transit time depends on carrier drift velocity & depletion region width.
$t_d = w/v_d$ where w = depletion region width, v_d = carrier drift velocity

Diffusion time can be seen by considering the photodiodes response time. This response time is described by rise time & fall time of detector output when detector is illuminated by a step input of optical radiation. The rise time measured from 10-90%, fall time is measured from 90-10%. For fully depleted photo diode rise time & fall time are same. They can be different at low bias levels where the photo diode is not fully depleted. The response time of partially depleted photodiode is shown in fig. the fast carriers allow the device output to rise to 50 percent of its maximum value in approximately 1 nsec, but the slow carriers cause a relatively long delay before the output reaches its maximum value.

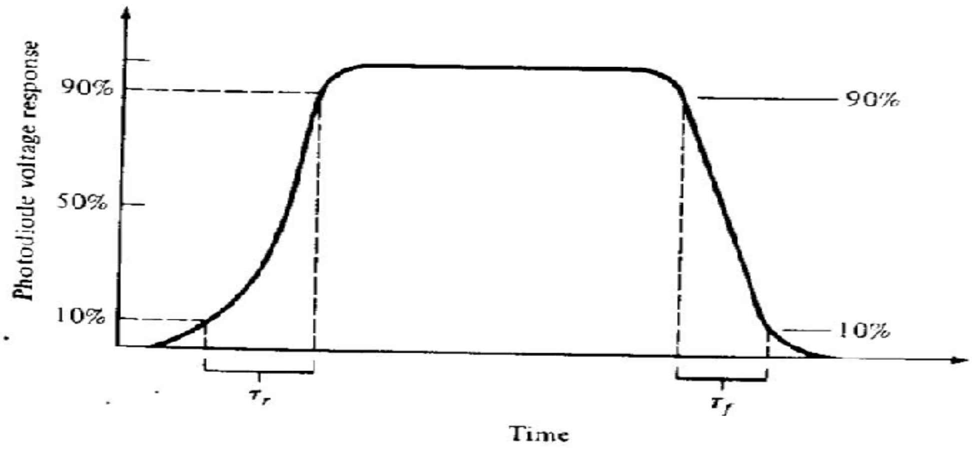


Figure 4.4: Photodiode response to an optical input pulse showing the 10 to 90% rise time and 90 to 10% fall time

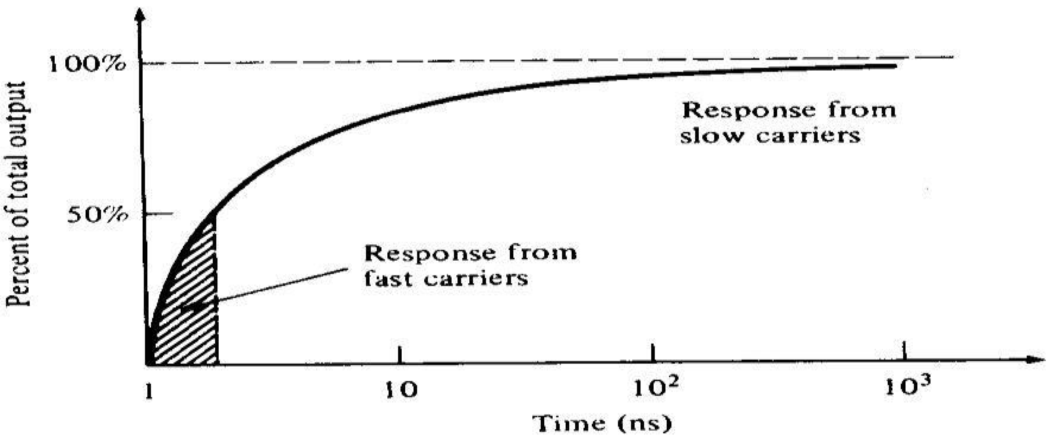


Figure 4.5: Response time of photo diode that is not fully depleted.

To achieve a high quantum efficiency, the depletion region width must be much larger than $1/\alpha_s$ i.e., $w >> 1/\alpha_s$

If the depletion layer is too narrow, any carriers created in the undepleted material would have to diffuse back into the depletion region before they could be collected. Devices with very thin depletion regions show distinct slow and fast response components as shown in figure 4.6.

The fast component in the rise time is due to carriers generated in the depletion region, where as slow component arises from diffusion of carriers that are created with a distance L_n from the edge of depletion region.

The diffusion of carriers that are with in a distance L_n of the depletion region edge appears as the slowly decaying tail at the end of the pulse. Also, if w is too thin, the junction capacitance will become excessive.

This excessiveness will then give rise to a large RC time constant, which limits the detector response time.

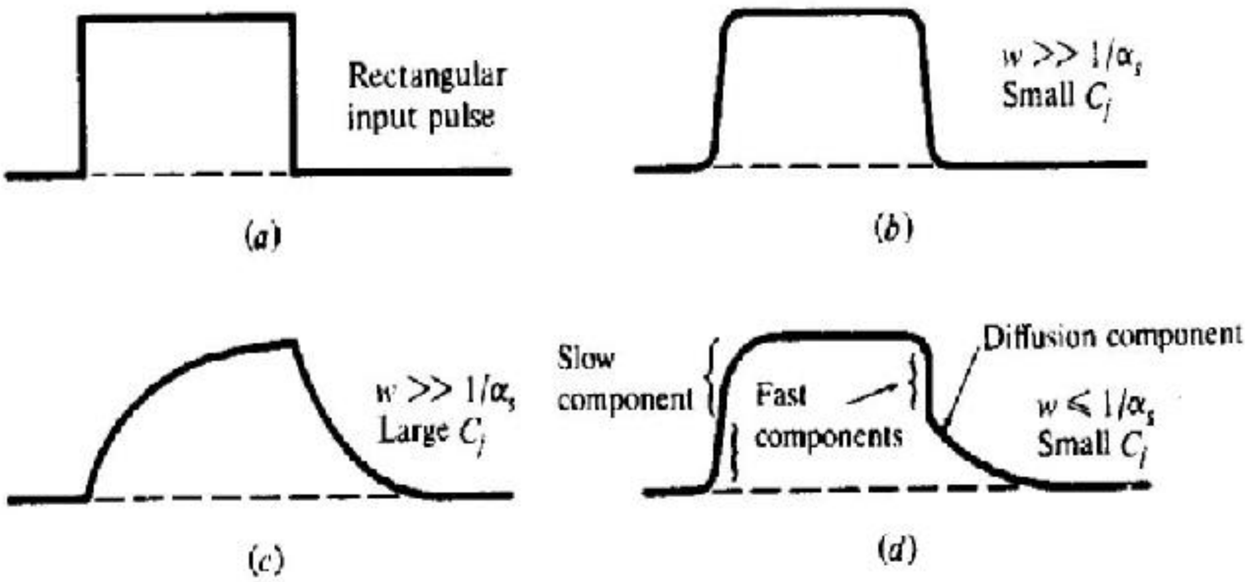


Figure 4.6: Photodiode pulse response under various detector parameters.

AVALANCHE MULTIPLICATION NOISE:

The avalanche process is statistical in nature, since not every photo generated carrier pair undergoes the same multiplication. If 'm' denotes the statistically varying, then $\langle m^2 \rangle = M^2$. where <> symbols denote an ensemble average.

The noise created in the avalanche process depends on the mean square gain $\langle m^2 \rangle$, the noise in an avalanche photodiode can be relatively high.

$\langle m^2 \rangle \cong M^{2+x}$ where x varies between 0 & 1 depending on the Photodiode material and structure.

The ratio of the actual noise generated in a avalanche photodiode to the noise that would exist if all carrier pairs were multiplied by M is called excess noise factor F

$$F = \langle m^2 \rangle / M^2$$

For injected electrons and hole, the excess noise factors are

$$F_e = \frac{k_2 - k_1^2}{1 - k_2} M_e + 2\left[1 - \frac{k_1(1 - k_1)}{1 - k_2}\right] - \frac{(1 - k_1)^2}{M_e(1 - k_2)}$$

$$F_h = \frac{k_2 - k_1^2}{k_1^2(1 - k_2)} M_h - 2\left[\frac{k_2(1 - k_1)}{k_1^2(1 - k_2)} - 1\right] + \frac{(1 - k_1)^2 k_2}{k_1^2(1 - k_2) M_h}$$

The weighted ionization rate ratio K1 & K2 take into account the non-uniformity of the gain and the carrier ionization rates in the avalanche region. They are given by

$$k_1 = \frac{\int_0^{W_M} \beta(x) M(x)\, dx}{\int_0^{W_M} \alpha(x) M(x)\, dx}$$

$$k_2 = \frac{\int_0^{W_M} \beta(x) M^2(x)\, dx}{\int_0^{W_M} \alpha(x) M^2(x)\, dx}$$

Normally, to first approximation K1 & K2 do not change much with variation in gain and can be considered constant and equal.

$$F_e = M_e\left[1 - (1 - k_{\text{eff}})\left(1 - \frac{1}{M_e}\right)^2\right]$$

$$= k_{\text{eff}} M_e + \left(2 - \frac{1}{M_e}\right)(1 - k_{\text{eff}})$$

for electron injection, and

$$F_h = M_h\left[1 - \left(1 - \frac{1}{k'_{\text{eff}}}\right)\left(1 - \frac{1}{M_h}\right)^2\right]$$

$$= k'_{\text{eff}} M_h - \left(2 - \frac{1}{M_h}\right)(k'_{\text{eff}} - 1)$$

for hole injection, where the effective ionization rate ratios are

$$k_{\text{eff}} = \frac{k_2 - k_1^2}{1 - k_2} \simeq k_2$$

$$k'_{\text{eff}} = \frac{k_{\text{eff}}}{k_1^2} \simeq \frac{k_2}{k_1^2}$$

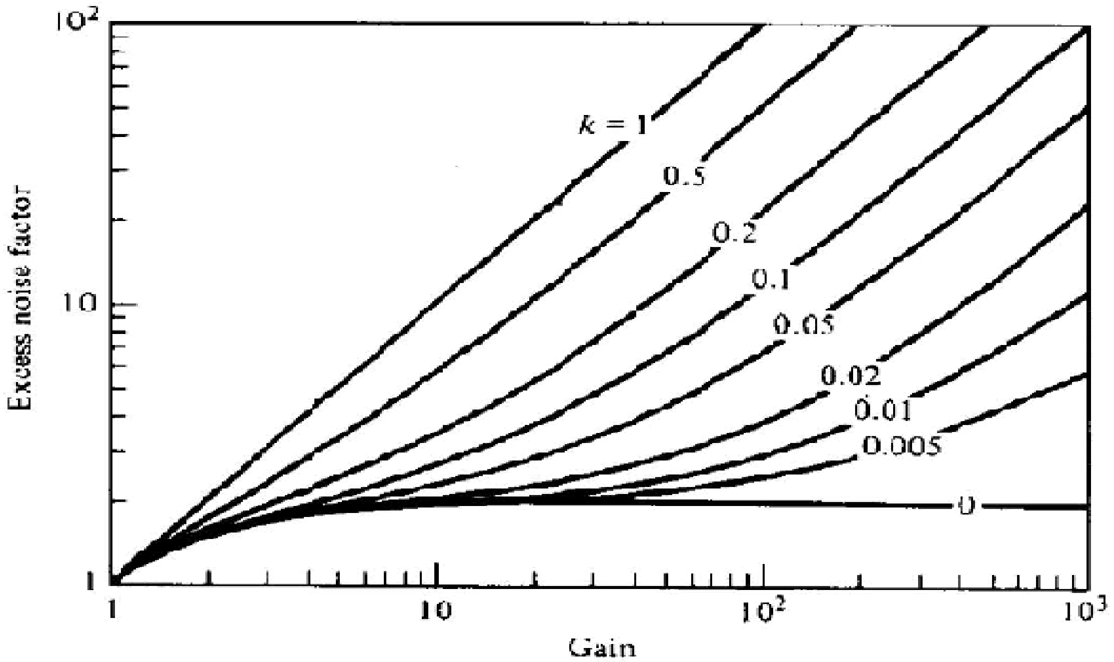


Figure 4.7: Variation of the electron excess noise factor F_e as a function of the electron gain for various values of effective ionization rate ratio.

From the empirical relationship for the mean-square gain given by $F = M^x$

Temperature Effect on Avalanche Gain:

The mechanism of Avalanche Photodiode is very temperature-sensitive because the temperature depends on the electron and hole ionization rates. Temperature dependence is particularly critical at high bias voltages and if temperature changes it cause large variations in gain. Temperature-dependent expression is given as:

$$M = \frac{1}{1-(V/V_B)^n}$$

Where, V_B=Breakdown voltage at which M goes to infinity, N varies between 2.5 and 7 depending on the material, $V=V_a-I_M R_M$, V_a=reverse bias voltage applied to the detector, I_M=Multiplied photocurrent, R_M=Photodiode series & detector load resistance

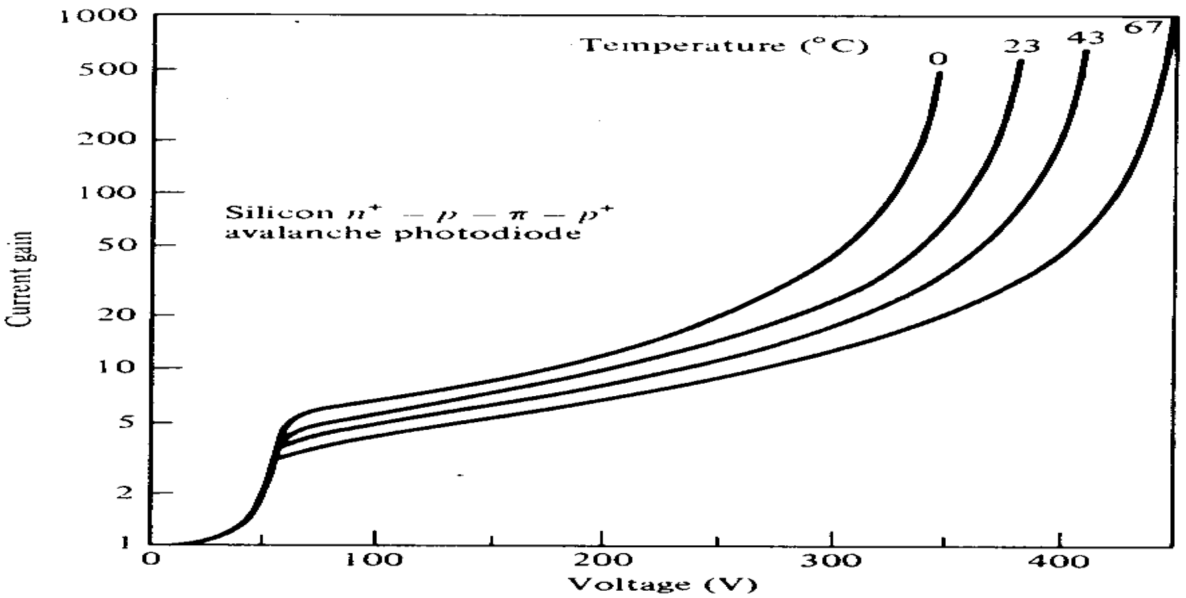
Break down voltage (V_B) interms of temperature is

$$V_B(T) = V_B(T_0)[1+a(T-T_0)]$$

The temperature dependence of the avalnce gain can be given as

$$n(T) = n(T_0)[1+b(T-T_0)]$$

Where, The constants a and b are positive for reach-through avalanche photodiodes



COMPARISION OF PHOTODETECTORS:

Some generic operating characteristics of Si, Ge & InGaAs photo diodes are summarized as follows.

For pin photo diodes:

Parameter	Si	Ge	InGaAs
WL range [nm]	400-1110	800-1650	1100-1700
Responsivity [A/W]	0.4-0.6	0.4-0.5	0.75-0.95
Rise time[ns]	0.5-1	0.1-0.5	0.05-0.5
BW[GHz]	0.3-0.7	0.5-3	1-2
Bias voltage[v]	5	5-10	5

For APD:

Parameter	Si	Ge	InGaAs
WL range [nm]	400-1110	800-1650	1100-1700
Avalanche gain	20-400	50-200	10-40
Rise time[ns]	0.1-2	0.5-0.8	0.1-0.5
Gain-BW[GHz]	100-400	2-10	20-250
Bias voltage[v]	150-400	20-40	20-30

FUNDAMENTAL RECEIVER OPERATION:

The design of optical receiver is much more complicated then optical transmitter because of receiver must be able to detect weak, distorted signal and make decision. OFC uses Intensity modulated direct detection system [IM-DDS] that use a binary on-off keyed [OOK] digital signal.

DIGITAL TRANSMISSION SYSTEM:

The function of optical transmitter is to convert the electrical signal to an optical signal. The optical signal emerging from the LED or LASER transmitter, 1 is represented by a pulse of optical power of duration Tb, whereas 0 is the absence of any light.

The optical signal that is coupled from the light source to the fiber becomes attenuated and distorted as it propagates along the fiber waveguide. Upon arriving at the end of fiber, a receiver converts the optical signal back to an electrical format. The first element is either a pin or APD, which produces an electrical current that is proportional to received optical power level. Since this electrical current is very weak, a front-end amplifier boosts it to a level that can be used by following electronics.

After amplification signal passes through a low-pass filter to reduce the noise that is outside of signal bandwidth. In final optical receiver module, a sampling circuit and decision circuit samples the signal level at the midpoint of each time slot and compares it with a certain reference voltage known as threshold level. If the received signal is greater then threshold level, 1 is said to have been received, other wise 0.

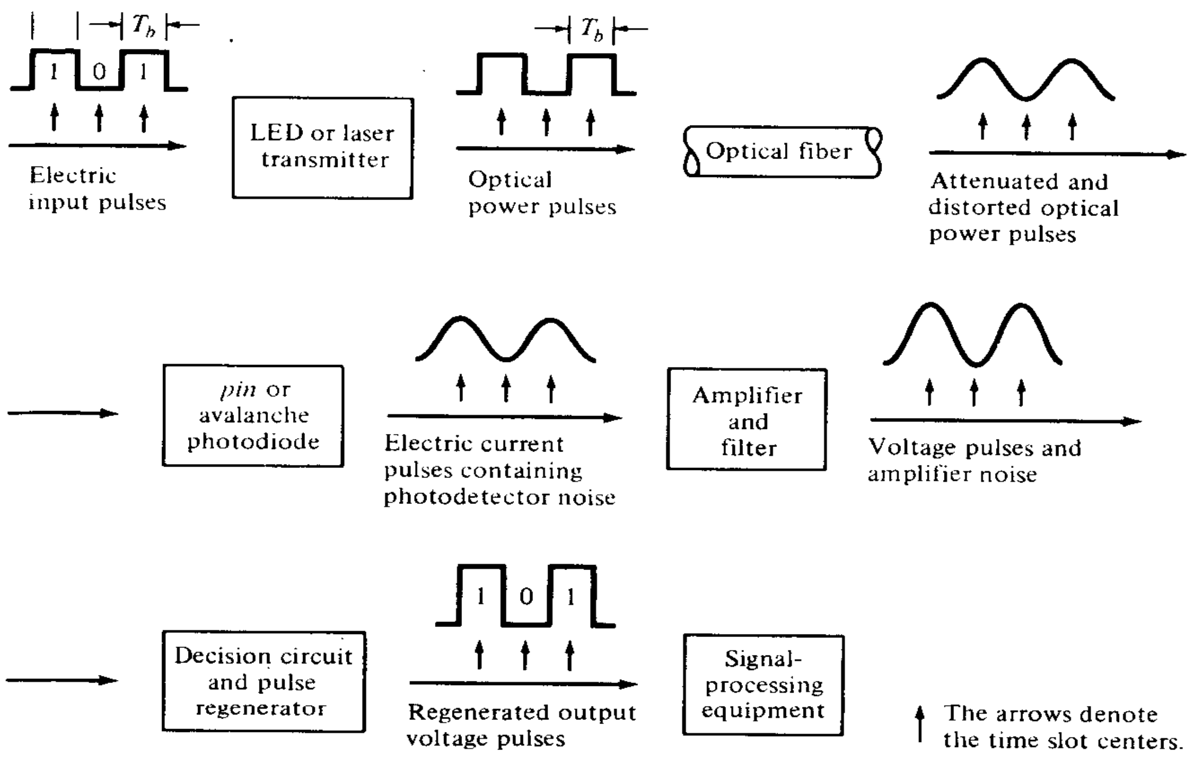


Figure 4.8: Signal path through an optical data link.

ERROR SOURCES:

Errors in detection mechanism can arise from various noises and disturbances associated with the signal detection system. The noise sources can be either external to the system or internal to the system. The noise is caused by the spontaneous fluctuations of current in electric circuits. Example for this fluctuations are quantum noise and thermal noise.

Another noise source is photodiode dark current, which is the current that flow through bias circuit of device when no light is incident on the photodiode. This is a combination of bulk and surface dark current.

Summary of photodetector noise sources

$$\langle i_Q^2 \rangle = 2qI_p BM^2 F(M)$$

$$\langle i_{DB}^2 \rangle = 2qI_D M^2 F(M) B$$

$$\langle i_{DS}^2 \rangle = 2qI_L B$$

$$\langle i_T^2 \rangle = \frac{4k_B T}{R_L} B$$

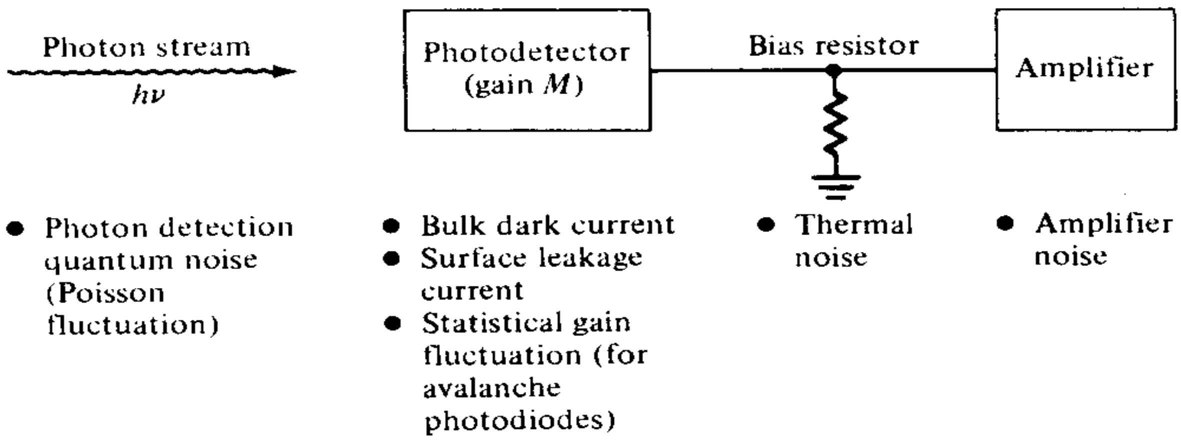


Figure 4.9: Noise Sources and disturbances in the optical pulse detection mechanism

If detector is illuminated by an optical signal P(t), then the no. of electron - hole pair generated in a time τ is

$$\overline{N} = \frac{\eta}{h\nu} \int_0^{\tau} P(t)\, dt = \frac{\eta E}{h\nu}$$

Where η is detector quantum efficiency, hv is the photo energy, E is energy received

FRONT-END AMPLIFIER:

Noise sources at the front end of a receiver dominate the sensitivity and bandwidth the goals generally are to maximize the receiver sensitivity while maintaining a suitable bandwidth. To achieve these goals, a basic concern in front end design is what load resistor R_L to choose because this parameter affects both the bandwidth and the noise performance.

Front-end amplifiers used in OFC systems can be classified into 3 categories

- LOW-IMPEDANCE
- HIGH-IMPEDANCE
- TRANSIMPEDANCE

LOW-IMPEDANCE [LZ] PREAMPLIFIER is most straightforward, but not the optimum preamplifier design. The Photo diode is configured into a LZ PAMP. Effective input resistance R_a, a bias resistance or load resistance R_b is used to match the amplifier impedance.

The total load resistance $R_L = R_aR_b/[R_a+R_b]$

The value of bias resistance in conjunction with amplifier input capacitance decides BW of amp. A small load resistance yields a large BW. But thermal noise dominates. Thus LZ amplifier can operate over a wide BW, they do not provide high receiver sensitivity because only a small signal voltage can developed across the total input impedance. This limits the use of these preamplifiers to special short-distance applications in which receiver sensitivity is not a major concern.

HIGH-IMPEDANCE [HZ] PREAMPLIFIERS: The thermal noise is inversely proportional to load resistance .The BW is inversely proportional to load resistance. Thus for high impedance front end, a high load resistance results in low noise but gives low receiver band width. Although equalizers sometimes can be implemented to increase BW, if the BW is much less than the bit rate, then such a front end amplifier cannot be used.

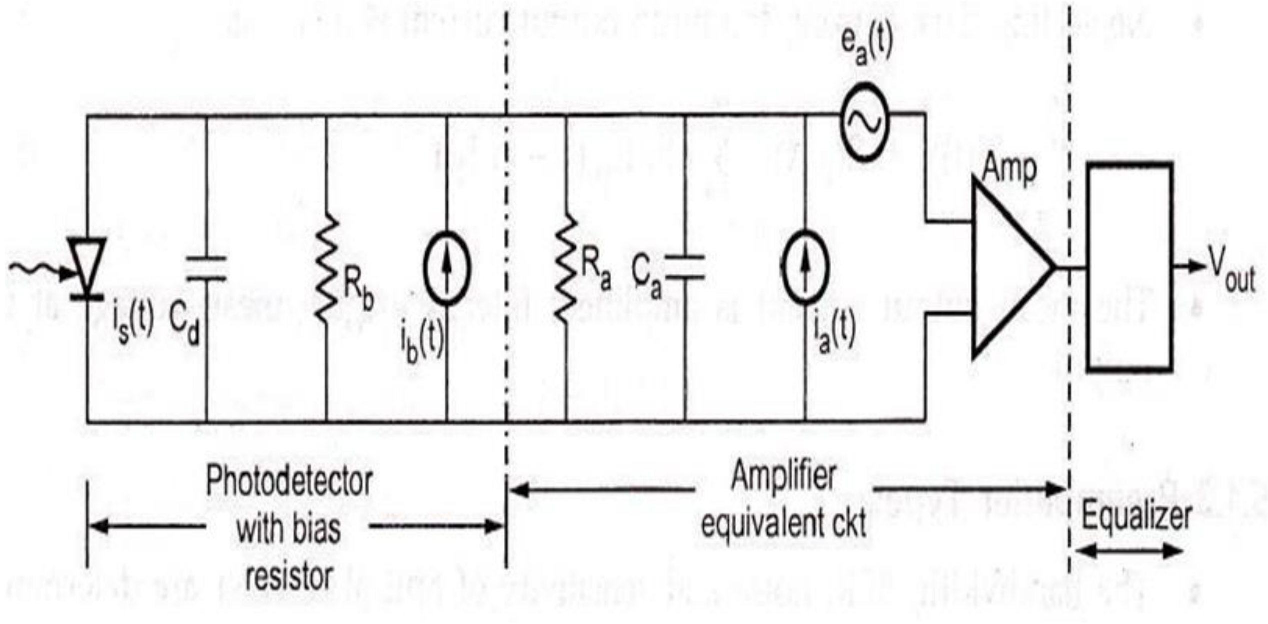


Figure 4.10: High Input-Impedance Preamplifier

TRANS-IMPEDANCE [TZ] PREAMPLIFIERS:

It is used to largely over comes the drawbacks of high impedance amplifier. In this case, R_L is used as a negative feedback resistor around an inverting amplifier. Now R_L can be large since the negative feedback reduces the effective resistance seen by the photodiode by a factor of G, so that $Rp = R_L/[G+1]$, where G is the gain of the amplifier. This means that compared to the high impedance design the trans impedance BW increases by a factor G+1 for the same load resistance.

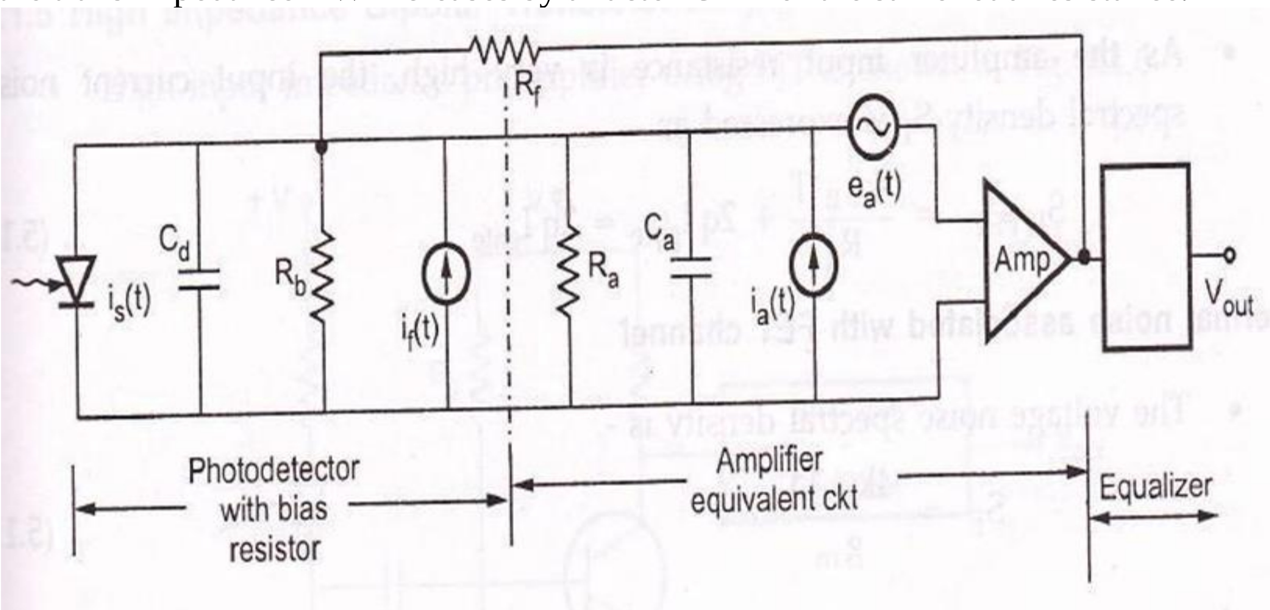


Figure 4.10: Transimpedance Preamplifier Equivalent Circuit

PROBABILITY OF ERROR:

Bit error rate is defined as ratio of no. of errors N_e occurring over a certain time interval t by the number of pulses N_t transmitted during this interval.

$$\text{BER} = \frac{Ne}{Nt}$$

This error rate depends on the SNR at the receiver. To compare the BER at the receiver we have to know the probability distribution of the signal at the equalizer output.

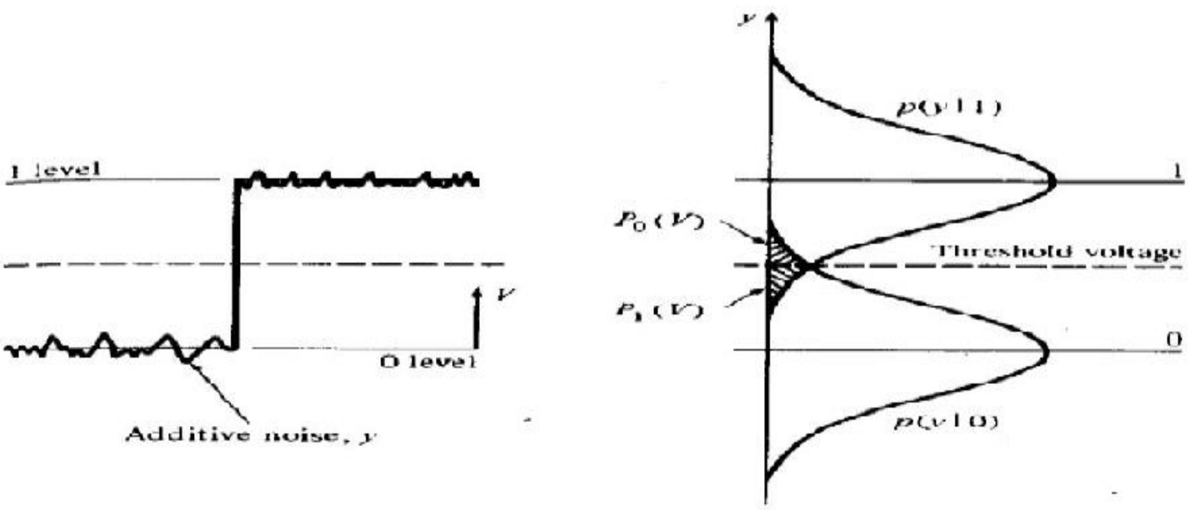


Figure 4.11: Probability distributions for 0 and 1 signal levels

The shapes of 2 probability distributions are shown in above figure 4.11. These are

$$P_1(v) = \int_{-\infty}^{v} p(y|1)\, dy$$

Which is probability that the equalizer output voltage is less than v when a logical 1 pulse is sent, and

$$P_0(v) = \int_{v}^{\infty} p(y|0)\, dy$$

which is the probability that the output voltage exceeds v when a logical 0 is transmitted.
If the threshold voltage is v_{th} then the error probability P_e is defined as

$$P_e = aP_1(v_{th}) + bP_0(v_{th})$$

The weighting factors a and b are determined by priori distribution of the data.
The probability of error $P_0(v)$ is the chance that the output voltage v(t) will fall some where between v_{th} and α, then

$$P_0(v_{th}) = \int_{V/2}^{\infty} p(y|0)\, dy = \int_{V/2}^{\infty} f_0(y)\, dy$$

$$= \int_{V/2}^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-v^2/2\sigma^2}\, dv$$

Where the subscript 0 denotes the presence of a 0 bit.
Similarly, probability of error that a transmitted 1 is misinterpreted as a 0

$$P_1(v_{th}) = \int_{-\infty}^{V/2} p(y|1)\, dy = \int_{-\infty}^{V/2} f_1(v)\, dv$$

$$= \frac{1}{\sqrt{2\pi\sigma^2}} \int_{-\infty}^{V/2} e^{-(v-V)^2/2\sigma^2}\, dv$$

Where subscript 1 denotes the presence of a 1 bit.

If the probabilities of 0 & 1 are equally likely then

$$P_e = \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{V}{2\sqrt{2}\sigma}\right)\right]$$

THE QUANTUM LIMIT:

In designing an optical system, it is useful to know what is fundamental physical bounds are on the system performance. Let us see what is bound for photo detector process. Suppose we have Ideal PD with unity quantum efficiency and no dark current. Given this condition, it is possible to find minimum received optical power required for a specific bit error rate performance in a digital system. This minimum optical power level is known as QUANTUM LIMIT.