Notes of

OPTICAL COMMUNICATION

EEC-701

UNIT-IV

For

Final Year students

Of

Electronics & Communication Branch

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OPTICAL COMMUNICATION (EEC-701) –UNIT-IV

Source to fiber power launching - Output patterns, Power coupling, Power launching, Equilibrium Numerical Aperture, Laser diode to fiber coupling. Optical detectors- Physical principles of PIN and APD, Detector response time, Temperature effect on Avalanche gain, Comparison of Photo detectors. Optical receiver operation- Fundamental receiver operation, Digital signal transmission, error sources, Receiver configuration, Digital receiver performance, Probability of error, Quantum limit, Analog receivers

SOURCE TO FIBER POWER LAUNCHING:

In implementing an optical fiber link, two of the major system questions are now to launch operation of optical power into a particular fiber from same type of luminescent source and how to couple optical power from the fiber to other. A measure of the 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:

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

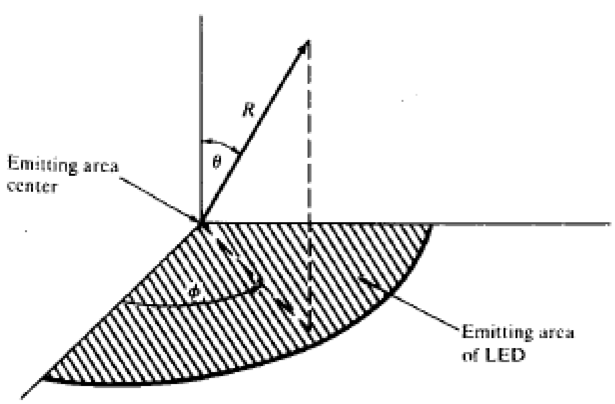
P_F: Power couple into the fiber

P_S: Power emitted from the light source

The launching and coupling efficiency depends on the type of fiber that is attached to the source and on the coupling process.

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/cm^2.

SOURCE OUTPUT PATTERN: The optical power accepting capability of a fiber is represented by a spatial radiation pattern of the source which is shown in figure:



Here the figure shows a spherical coordinate system characterized by R, θ and ϕ with the polar axis. The radiance may be a function of both θ and ϕ and can also vary from point to point on the emitting surface.

1). Surface emitter LED can be characterized by this output pattern, which means the source is equally bright when viewed from any direction. The power delivered at an angle θ, varies as cosθ because the projection area of emitting surface varies, so the emission area pattern follows:

$$\boldsymbol{B(\theta, \phi) = B_0 \cos\theta}$$

B_0: radiance along the normal to the radiating surface.

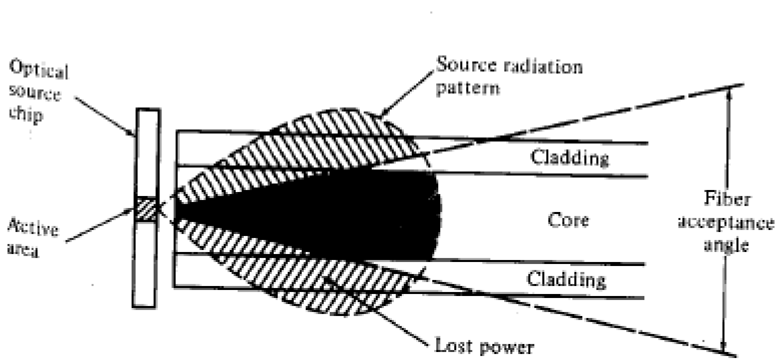
2). For edge emitter LED, and laser diodes, more complex emission pattern exists. These devices have different radiance $B(\theta, 90^0)$ and $B(\theta, 0^0)$ in the planes parallel and normal. In general,

$$\frac{1}{B(\theta,\phi)} = \frac{\sin^2\theta}{B_0 \cos^T\theta} + \frac{\cos^2\theta}{B_0 \cos^L\theta}$$

where, L and T represents lateral power and transverse power distribution.

For edge emitter, L=1
for laser diode, L=100

POWER COUPLING: The optical power coupling of any fiber can be calculated by the symmetric source of brightness (B), area A_s and solid acceptance angle Ω_s



Here, the fiber end face is centered over emitting surface of the source and is positioned as close as possible.
So, the power coupled is:

$$P = \int_{A_f}^{0} dA_s \int_{\Omega_f}^{0} d\Omega_s B(A_s, \Omega_s)$$

$$P = \int_0^{r_m} \int_0^{2\pi} \left[\int_0^{2\pi} \int_0^{\theta_{0,max}} B(\theta, \phi) sin\theta d\theta d\phi\right] d\theta_s rdr$$

r_m: upper integration limit of radiation

If the source radius r_s is less than fiber core radius a, then $r_m = r_s$; and for sources areas larger than the fiber core area, r_m= a.
For SLED, $r_s < a$, so,

$$P = \int_0^{r_s} \int_0^{2\pi} \left[2\pi B_0 \int_0^{\theta_{0,max}} cos\theta\ sin\theta\ d\theta\right] d\theta_s rdr$$

$$P = \pi B_0 \int_0^{r_s} \int_0^{2\pi} sin^2\theta_{0,max} d\theta_s rdr$$

$$P = \pi B_0 \int_0^{r_s} \int_0^{2\pi} NA^2 d\theta_s rdr$$

POWER LAUNCHING VERSUS WAVELENGTH: The power launched into a fiber depends upon the brightness of the source, which is radiance. So a number of modes can propagate in a multimode graded index fiber of core size 'a' and index profile 'α' is :

$$N = \frac{\alpha}{\alpha+2}\left(\frac{2\pi a n_1}{\lambda}\right)^2 \Delta$$

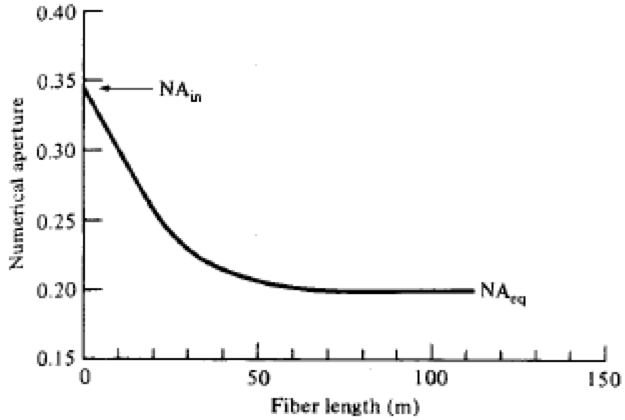
So, the radiated power per mode, P_s/M, from a source at a particular wavelength is given by,

$$\boldsymbol{\frac{P_s}{M} = B_0 \lambda^2}$$

B_0: radiance

EQUILIBRIUM NUMERICAL APERTURE: In a optical fiber setup, the losses occurs in the first few tens of meters of a multimode system. To achieve a low coupling loss, this should be connected to a system fiber that has a identical NA and core diameter. A certain amount of optical power is lost at the connecting mechanism of the fiber setup.
If the light emitting area of the LED is less than the cross sectional area of the fiber core, the power coupled into the fiber is NA_{in} and when the optical power measured in long multimode fibers after the launched mode have come to equilibrium, the effect of equilibrium NA become apparent. At this point optical power in the fiber:

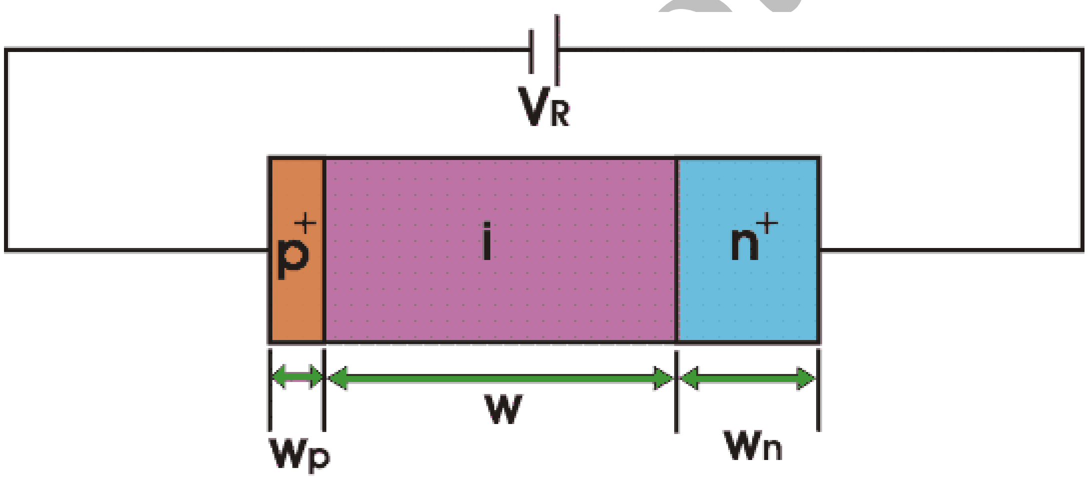
$$P_{eq} = P_{50}\left(\frac{NA_{eq}}{NA_{in}}\right)^2$$



LASER DIODE TO FIBER COUPLING: In edge emitting LED, the angular output distribution of the laser is greater than the fiber acceptance angle, and since the laser emitting area is much smaller than the fiber core, spherical or cylindrical lenses can also be used to improve the coupling efficiency between edge cutting laser diodes and optical fibers. This is also known as vertical cavity surface emitting laser (VCSELs).

<u>PHOTODETECTORS:</u>

1. PIN PHOTODETECTOR:



The most common semiconductor photo detector is the PIN photodiode.

The device structure consists of p and n regions separated by a very lightly doped n type intrinsic region. In normal operation, a large reverse bias voltage is applied across the device so that the intrinsic region is fully depleted of carriers.

<u>Operation:</u> When an incident photon has energy greater than or equal to the band gap energy of the semiconductor material, the photon can give up its energy and excite an electron from the VB to CB. The electrons and holes are called photo carriers. The photo detector is normally designed so that these carriers are intentionally added in the depletion region, where most of the incident light is absorbed. This gives rise to a current flow in an external circuit, with one electron flowing for every carrier pair generated. This current is known as the photocurrent.

The charge carriers move a distance L_N or L_P for electrons and holes. This distance is known as diffusion length and the time taken for an electron and hole to recombine is known as carrier lifetime (τ_N and τ_P). The lifetime and the diffusion length are related as:

$$L_N = (D_N \tau_N)^{1/2}$$

$$L_P = (D_P \tau_P)^{1/2}$$

The quantum efficiency 'η' is the number of the electron hole carrier pairs generated per incident photon of energy hν and is given by:

$$\eta = \frac{No.of\ electron-hole\ pair\ generated}{No.of\ incident\ photons}$$

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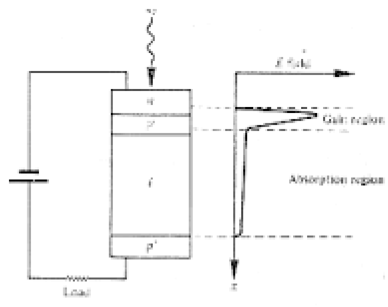
$\eta = \frac{I_P/q}{P_{in}/h\nu}$

I_P: Photo current

P_{in}: Incident optical power

2. **AVALANCHE PHOTODIODE:**



Avalanche photodiode (APD) internally multiply the primary signal photocurrent before it enters the input circuitry of the following amplifier. This increases receiver sensitivity, since the photocurrent is multiplied before encountering the thermal noise associated with the receiver circuit. In order for carrier multiplication to take place, the photo generated carriers must traverse a region where a very high electric field is present. In this high field region, a photo generated electron or hole can gain enough energy so that it ionizes bound electrons in the valance bond upon colliding time. This is known as **impact ionization.**

The newly created carriers are also accelerated by high electric field, thus known as avalanche effect.

The average number of electron hole pair created by a carrier/unit distance travelled is called ionization rate. The multiplication M for all carriers generated in the photodiode is defined by:

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

I_M: Multiplied carrier current

I_P: Primary current

DETECTOR RESPONSE TIME: The response time of a photodiode together with its output circuit depends upon,

a). The transit time of the photo carriers in the depletion region.

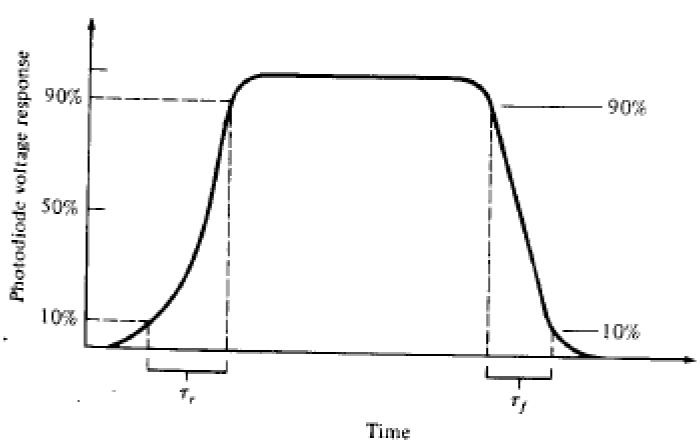
b). The diffusion time of the photo carriers generated outside the depletion region.

c). The RC time constant of the photodiode.

The photodiode parameters responsible for these three factors are absorption coefficient α_S, the depletion region width ω, the photodiode junction and package capacitances, the amplifier capacitance. The transit time depends on the carrier drift velocity v_d and the depletion layer width 'ω'.

$\boldsymbol{t_d = \frac{\omega}{v_d}}$

The photodiode response time to an optical input pulse is



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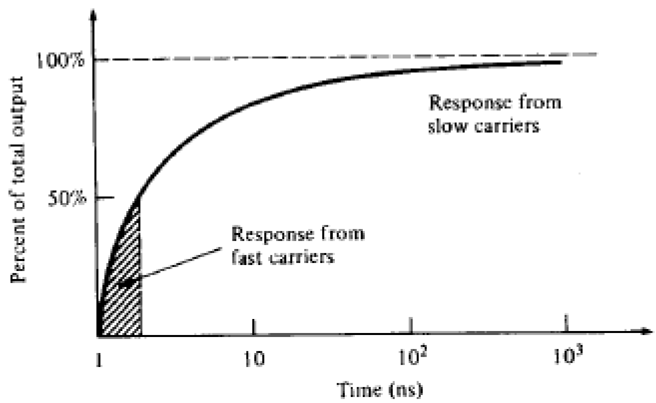


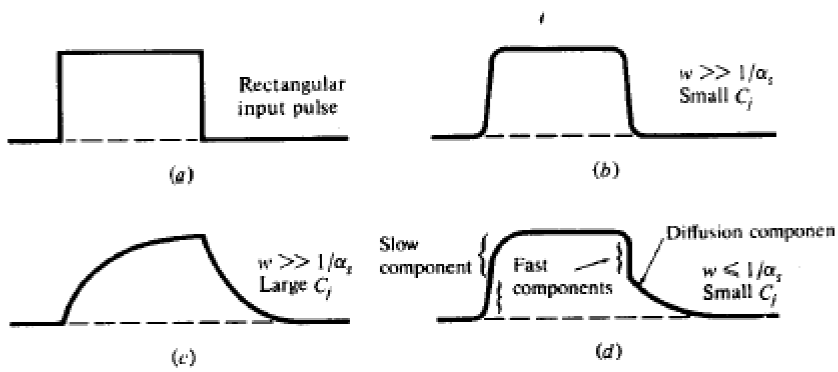
τ_r: Rise time life time

τ_f : fall time life time

Junction capacitances:

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

Now, photodiode pulse responses under various detector parameters:



TEMPERATURE EFFECT ON AVALANCHE GAIN: The gain mechanism of an avalanche photodiode is very temperature sensitive because of the dependence of the electron and hole ionization rates. This temperature dependence is particular critical at high bias voltage, where small changes in temperature can cause large variation in gain.

To maintain a constant gain as the temperature changes, the electric filed in the multiplying region of the p-n junction must also be changed, which adjusts the applied bias voltage on the photo detector when the temperature changes.

The temperature dependent expression for gain is:

$$M = \frac{1}{1-\left(V/V_B\right)^{\eta}}$$

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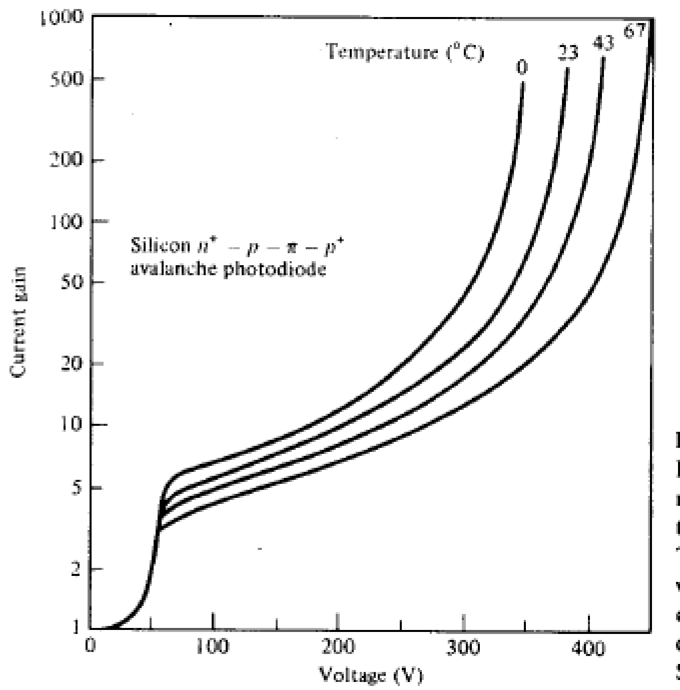
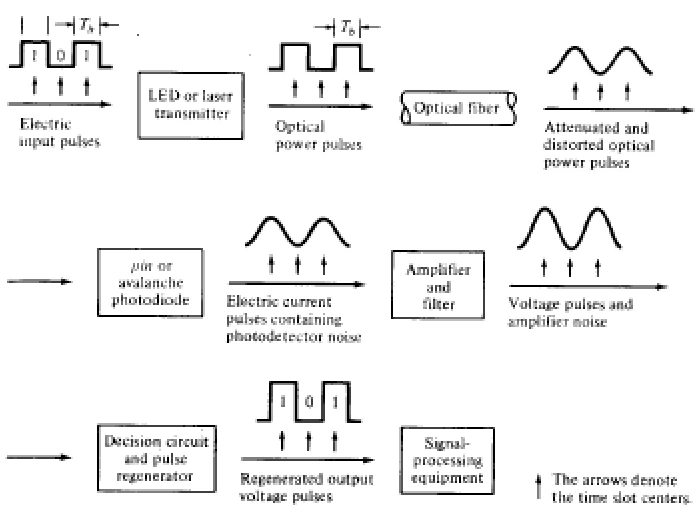


V_B: Breakdown voltage
η: varies between 2.5 to 7, as per material
$\boldsymbol{V = V_a - I_M R_M}$
V_a: reverse bias voltage
I_M: multiplies photocurrent
R_M: resistance
So, the breakdown voltage:
$\boldsymbol{V_B = V_B(T_0)[1 + a(T - T_0)]}$

<u>OPTICAL RECEIVER OPERATION:</u>
The design of an optical receiver is much more complicated than that of an optical transmitter because the receiver must be able to detect weak signals, distorted signals and make decisions on what type of data was send based on an amplified and reshaped version of this distorted signal.

DIGITAL SIGNAL TRANSMISSION:



The transmitted signal is a two level binary data stream consisting of either a 0 or a 1 in a time slot of duration T_b. This time slot is referred to as a bit period. One technique for sending binary data is amplitude shift keying (ASK) or on-off key (OOK). The resultant

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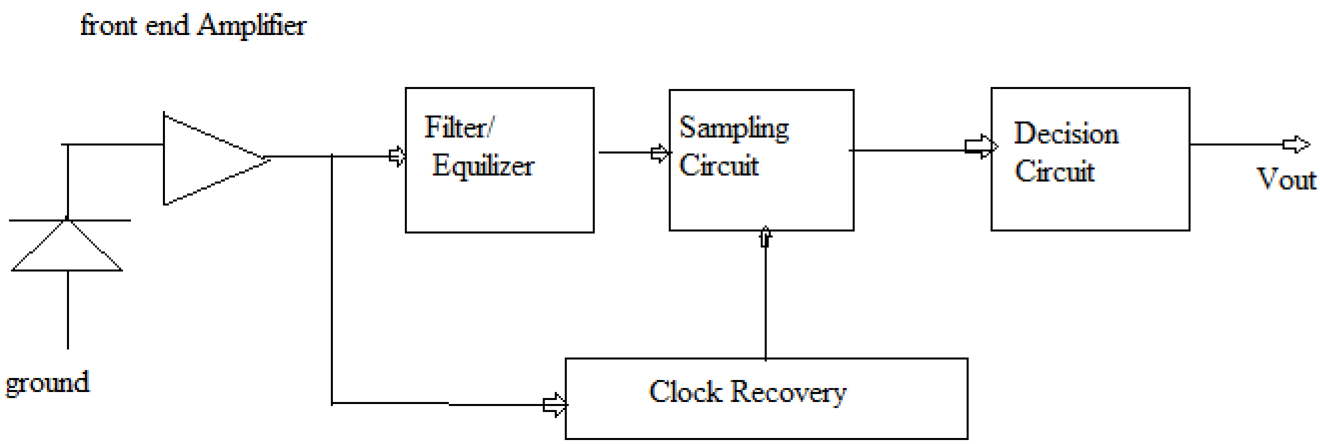
signal wave thus consists of a voltage pulse of amplitude V relative to the zero voltage level when a binary 1 occurs and a zero voltage level space when a binary 0 occurs. Depending on the coding scheme to be used a binary 1 may or may not fill the time slot T_b.
The function of the optical transmitter is to convert the electric signal to an optical signal, thus in the optical signal emerging from the LED or laser transmitter 1 is represented by a pulse of optical power (light) of duration T_b, 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 the fiber, a receiver converts the optical signal back to an electrical format.

BASIC COMPONENTS OF AN OPTICAL RECEIVER:



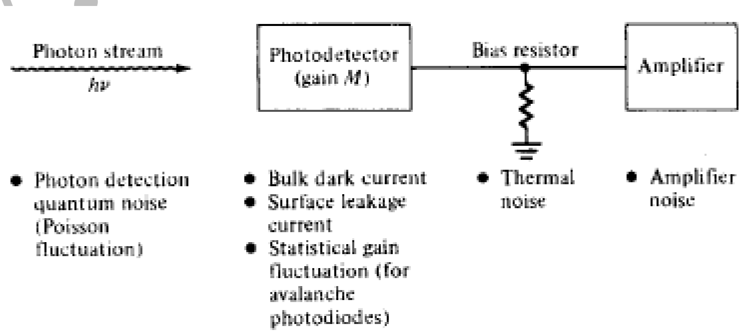
As per the diagram, the first element is either a pin or an avalanche photodiode, which produces an electric current that is proportional to the received power level. Since this electric current is typically very weak, a front end amplifier boosts it to a level that can be used by the following electronics. After amplification, it is passed through a low pass filter to reduce the noise that is outside of the signal bandwidth. To minimize the effect of ISI, the filter can reshape the pulses that have become distorted as they travelled through the fiber. This function is called equalization, because it equalizes or cancels pulse spreading effect. Now a decision circuit samples the signal level with a certain reference voltage known as the threshold level.

If received signal level is > Threshold level → 1 received

If received signal level is < Threshold level → 0 received

To accomplish this bit interpretation, the receiver must know where the bit boundaries are. This is done with the assistance of a periodic waveform called a 'clock', which has a periodically equal to the bit interval. Thus this function is called 'clock recovery' or 'timing recovery'.

ERROR SOURCES:



Errors in the detection mechanism can arise from various noises and disturbance associated with the signal distortion system.
The noise sources can be either external to system or internal to the system.
The internal noise is caused by the spontaneous fluctuations of current or voltage in electric circuits. Shot noise arises in electronic devices because of the discrete nature of current flow in the device . Thermal noise arises from the random motion of electrons in a conductor.
When using an APD, an additional shot noise arises from the statistical nature of the multiplication process. The noise level increases

with larger avalanche gain M. additional photo detector noises come from the dark current and leakage current.
If the detector is illuminated by an optical signal P(t), then the average number of E-H pair N generated in a time τ is :

$$\bar{N} = \frac{\eta}{hv}\int_0^\tau P(t)dt = \frac{\eta E}{hv}$$

η: detector quantum efficiency
τ: time interval

The actual number of E-H pairs n that are generated from the average according to the poission distribution:

$$P_r(n) = \frac{\bar{N}^n e^{-\bar{N}}}{\eta!}$$

where $P_r(n)$ is the probability that n electrons are emitted in an interval τ.
So, the express noise factor due to avalanche multiplication,

$$F(M) = kM + \left(2 - \frac{1}{M}\right)(1-k)$$

$$F(M) \cong M^x$$

where, k : ionization ratio
x : photodiode material range (0 & 1)

DIGITAL RECEIVER PERFORMANCE: In a digital receiver the decision circuit output signal voltage $V_{OUT}(t)$ would always exceed the threshold voltage when a 1 is present and would be less than the threshold when no pulse was sent. But in actual, deviation occurs due to various noises, interference and undistinguishable light pulses.

PROBABILITY OF ERROR: There are several ways of measuring the rate of error occurrences in a digital data stream. A simple approach for this is bit error rate (BER).

$$BER = \frac{N_e}{N_t} = \frac{N_e}{Bt}$$

where, N_e: error occurring in a certain time interval τ
N_t: Pulse transmitted during this interval
B: Bit rate = $\frac{1}{T_b}$

In telecommunication, the error rate depends upon the SNR (Range 10^{-9} to 10^{-12}). The system error rate requirement and the receiver noise levels set a lower limit on the optical signal power level that is required at the photo detector.
To compute the BER at the receiver, the probability distribution is required at the equalizer output. The signal is digital so it can be either 0 or 1.

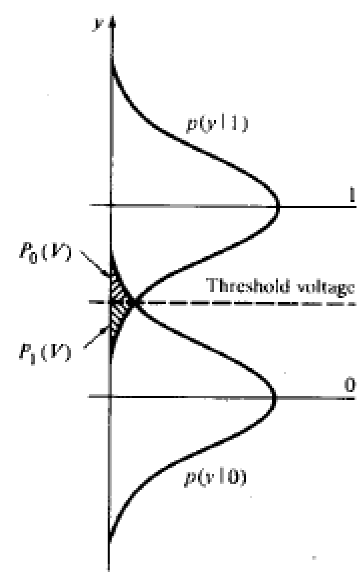
$$P_1(v) = \int_{-\infty}^{v} P(y/1)dy \qquad (1)$$

$$P_0(v) = \int_{v}^{\infty} P(y/0)dy \qquad (2)$$

where v is the level voltage.
If the threshold voltage is v_{th}, then the error probability P_e is defined as:

$$\boldsymbol{P_e = aP_1(v_{th}) + bP_0(v_{th})} \qquad (3)$$

a & b : probabilities that either a 1 or 0
eg for unbiased data with equal 0 & 1, a=b=0.5



RECEIVER SENSITIVITY: Optical communication system use a BER value to specify the performance requirement for a particular transmission link application eg SONET/SDH network BER→10^{-10} and Ethernet & fiber channel require BER→10^{-12}. To achieve a desired BER at a given data rate, a specific minimum average optical power level must arrive at the photo detector. The value of this minimum power level is called the receiver sensitivity.

The receiver sensitivity is found from the average power contained in a bit period for the specified data rate as:

$$P_{sensitivity} = \frac{P_1}{2} = J_1/2RM$$

R: unity gain responsibility

M: gain of photodiode

If there is no optical amplifier in a fiber transmission link, then thermal and shot noise dominate the noise effect in the receiver. Therefore, assuming there is no optical power in a received zero pulse, the noise variances for 0 and 1 pulse respectively are:

$$\sigma_0{}^2 = \sigma_T{}^2$$

$$\sigma_1{}^2 = \sigma_T{}^2 + \sigma_{shot}{}^2$$

In a photodiode, the noise figure F(M) and electrical bandwidth B_e of the receiver is assumed to be half the bit rate, so the thermal noise current variance is :

$$\sigma_T{}^2 = \frac{4R_BT}{R_L} = f_n\frac{B}{2}$$

After substituting the operating values, R_L=200Ω, T=300^0K, f_n=3dB, σ_T=9.10×$10^{-12}B^{1/2}$, BER=10

$$\boldsymbol{P_{sensitivity} = \frac{7.37}{M}\left[5.6\times10^{-19}MF(M)B + 9.10\times10^{-12}B^{1/2}\right]}$$

QUANTUM LIMIT: In designing an optical system, the fundamental physical bounds must be known for the system performance. Suppose that we have an ideal photo detector which has unity quantum efficiency and which produces no dark current, no E-H pair generated in the absence of an optical pulse. Given this condition, it is possible to find the minimum received optical power required for a specific BER performance in a digital system. This minimum received power level is known as Quantum limit.

Assume that an optical pulse of energy E falls on the photo detector in a time interval τ, this can only be interpreted by the receiver as a 0 pulse if no E-H pairs are generated, the probability, n=0.

$$\boldsymbol{P_r(0) = e^{-\bar{N}}}$$

ANALOG RECEIVERS: The usage of fiber optics transmission link becomes wide with analog links. This range 4 kHz voice channels to microwave links operating in the multigigahertz region.

The analog technique is used in amplitude modulation, where a time varying electric signal s(t) is used to modulate an optical source directly about some bias point defined by the bias current I_B. The transmitted optical power P(t) is:

$$P(t) = P_t[1 + ms(t)] \quad (1)$$

where, P_t: transmission power

m : modulation index

$$m = \frac{\Delta I}{I_B}$$

At the receiver end, the photocurrent generated by the analog optical signal is:

$$i_s(t) = RMP_r[1 + ms(t)]$$

$$i_s(t) = I_pM[1 + ms(t)]$$

where, $I_p = RP_r$= primary photo current

The mean square signal current at the photocurrent output is:

$$\langle i_s{}^2\rangle = \frac{1}{2}(RM_mP_r)^2$$

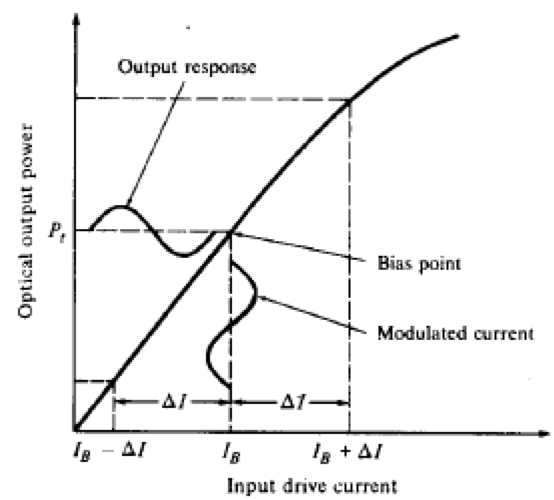
$$\langle i_s{}^2\rangle = \frac{1}{2}\left(M_mI_p\right)^2$$

and the mean square noise current is:

$$\langle i_s{}^2\rangle = 2q\left(I_p + I_D\right)M^2F(M)B_e + 2qI_LB_e + \frac{4R_BTB_e}{R_{eq}}$$

For SNR,

$$\boldsymbol{\frac{S}{N} = \frac{\langle i_s{}^2\rangle}{\langle i_N{}^2\rangle} = \frac{m^2I_P}{4qB_e} = \frac{m^2RP_r}{4qB_e}}$$



Since the SNR in this case is independent of the circuit noise, it represents the fundamental or quantum limit for analog receivers.

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