OPTICAL DETECTOR

1-Introduction: -

Photodetector converts the information transmitted via optical signals to corresponding electrical signals, which are then processed further to perform the desired functions.

The basic principle of photodetectors is that they absorb incident photons, which produce electrical charge carriers, i.e., electron and/or holes. The flow of charge carriers produces the electrical signals. The diameter of the cores of the optic fibers used in communications are between 10 and 50 micrometer, and their attenuation range between 5 and 20 dB/Km. the light sources which can couple with these optic fibers are light-emitting diodes (LEDs), injection laser diodes (ILDs), and neodymium-doped yttrium-aluminum-garnet (Nd:YAG) crystals pumped by LEDs.

The amount of light which can be coupled into the fibers at the source end ranges from a few microwatts. The light emerging at the detector end after traversing perhaps several kilometers of the optic fiber is attenuated. To detect such weak optical signals, the photodetectors have to meet the following criteria: -

1- *High sensitivity*. The photodetectors must be able to detect weak optical signals, i.e.; the quantum efficiency should be high.
2- *High speed*. The response of the photodetectors to optical signals should be fast. They should have sufficient bandwidth to handle the information rate. Also, this response of the photodetectors should be linear with respect to the optical signals over a wide range of amplitudes.
3- *Large signal-to-noise ratio*. The detectors should also have low dark currents.
4- Room temperature operation
5- High reliability and long-term stability
6- Material compatibility. The material and the technology used to fabricate photodetectors should be compatible with monolithic IC technology and should interface with microprocessor.

Compatibility requirement involve considerations of the fiber, power supply, electronic circuitry needed to amplify and process the signal, physical dimensions, etc. A variety of photodetectors are potentially applicable to optical communications systems, but only a few of these can be seriously considered for this application. Various types of photodetectors that have been used for the detection of photons in a variety of applications, including optical communications can be classified as follows:-

Semiconductor detector: -

Examples of semiconductor detectors are photoconductive devices, conventional and avalanche photodiodes, phototransistors, and charge- coupled devices (CCDs). These devices can detect impinging photons and contain a depleted semiconductor region with a high electric field that serves to separate photon-exited electron-hole pairs. Such a depletion region can be obtained, for example, by reverse biasing of a p-n junction, reverse biasing of a Schottky or surface barrier, or biasing of an MOS capacitor in a mode suitable for depletion of carriers in the semiconductor. The speed with which the photon-carrier interaction takes place determines in part the frequency response of the devices. Hence, CCDs, for example, cannot be considered for high-data-rate operation.

The most important semiconductor detectors: -

1- Photoconductor
2- Depletion layer photodiode
   a) PN photodiode
   b) PIN photodiode
   c) Schottky barrier photodiode
3- P-n junction avalanche photodiode (APD)
4- Schottky barrier photodiode
5- Electroabsorption APD

Nonsemiconductor detectors:

Examples of vacuum photodetectors are photomultipliers and image intensifiers. The photocathode is the key element in a photomultiplier, which detects photons through the process of photoelectric emission of an electron from the photocathode. The most useful materials for vacuum devices are the alloys Ag-O-Cs, Cs-Te, K-CS-Sb, GaAs-Cs_2O, and Na_2KSb-CS. The last is the most commonly used photocathode material because of its broad spectral response, relatively high sensitivity, and low dark current. Most of these devices, however, lack the frequency response required of high-data-rate detectors. The most important nonsemiconductor detectors are photomultipliers and micro channel plates.

2-Detector Characteristics: -

Of these listed above, the most commonly used photodetectors in optical communications are the silicon PIN and avalanche photodiodes. Other semiconductor materials are under development and investigation, and should preferably meet the following two criteria:

1- The energy band gap of, and/or the Schotty barrier height of, the semiconductor should be slightly smaller than the energy of the photons at the longest wavelength of the light used for communication.

2- Under ideal conditions, only one type of carrier, i.e., either electrons or holes, should undergo ionizing collisions in the semiconductor. If this cannot be achieved, the ionization coefficient of one type of carrier in the semiconductor should dominant the other.

To evaluate the performance of a photodetector, the following questions need to be answered:

1. How efficient is the detection of the photons in the photodetector? How many charged carriers are produced in the photodetector by the incident photons?
2. Does the photodetector increase the number of charged particles (produced initially on photon absorption) as they are transported out of the photodetector to the external

circuitry? What is the mechanism of this gain in, or multiplication of, the number of carriers?
3. When the above charged carriers flow out of the photodetector to the external circuitry to produce the output signals, how well do the output electrical signals correspond to, or faithfully reproduce, the input signals? How clean are these output signals? How much higher are these as compared to the noise characteristic of a given type of photodetector and the external circuitry? Also, how fast is the response of the photodetector?

The physical mechanisms of a few types of photodetector will be discussed. The general expression for the total photocurrent I_t produced by a photodetector when the incident optical power is P_T can be written

$$I_t = M\,(q\eta P_t/h\nu + I_d) \qquad (1)$$

Where q is the unit electronic charge, η the quantum efficiency, M the multiplication (gain) factor, P_T the incident optical power, h Planck's constant, v the frequency of the photons, and I_d the dark current of the photodetector.

The quantum efficiency η, the multiplication factor M, the dark current I_d, and consequently the total photocurrent I_t depend strongly on the material and the design of the photodetector and on the wavelength of light used. The choice of the material and the design depends on the wavelength range and the application of the photodetector. The parameters defined in the following sections are used to evaluate the performance of the photodetectors.

1-*Quantum Efficiency*

Quantum efficiency η is the percentage of incident photons absorbed by the photodetector to liberate charged carriers. In general, η depends on several factors and can be written

$$\eta = f(\lambda, \omega, \alpha_c, E_G, \alpha_n, \alpha_p, t, G_d) \qquad (2)$$

Where λ is the wavelength of light, ω the modulation frequency of incident light, α_c the absorption coefficient of light (which is also a function of λ) in the detector material, E_G the forbidden energy band gap of the detector material, α_n the ionization coefficient of electrons in the detector material, α_p the ionization coefficient of holes in the detector material, T the temperature of operation of the detector, and G_d the geometry of the detector. The geometry determines the total path length of light in the detector, its location with respect to the depletion layer, and the electric field seen by the carriers (which affect α_n and α_p).

2-*Multiplication Factor*

The multiplication factor M is a measure of the gain provided by the photodetector. It is defined as the ratio

$$M = I/I_p \qquad (4.3)$$

Where I is the total output current at the operating voltage (where carrier multiplication occurs) and I_p the total primary current at low voltage (where carrier multiplication does not occur).

3-*Total Noise Equivalent Power*

The total noise equivalent power (TNEP) of a photodetector is a measure of the minimum detectable signal in the presence of the noise inherent in the detection and multiplication processes. It is defined as the amount of light (root mean square, rms, of the sinusoidally modulated radiant power) incident on the active area of the photodetector which will produce an output signal equal to the noise output (rms noise voltage). It is usually stated in nanowatts

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4-*Noise Equivalent Power*

The noise equivalent power (NEP) is defined as the TNEP normalized to a 1 Hz bandwidth, stated as W/Hz.

5-*Responsivity*

The responsivity of a photodetector (R_p) is the average output current divided by the average incident radiant power,

$$R_p = I/P \qquad (3)$$

6-*Signal-to-Noise Ratio*

As the name implies, the signal-to-noise ratio (S/N) of the photodetector is the ratio of the signal produced by the incident light under the given operating conditions to the electrical noise inherently present in the detector under those operating conditions. It is one of the most important criteria used to evaluate detectors.

7-*Response Time*

The response time (τ_R) of the photo-detector is the transit time of the charged carriers to the output terminals. It is dependent on the characteristics of the photo-detector as well as on the external circuitry. In a simplified model, the response time (τ_R) is the rms sum of the total charge collection time and the RC (resistance-capacitance) time constant due to the series and the load resistances and detector and stray capacitances. The (τ_R) is a measure of how fast the photo-detector responds to the variations in the input optical signals.

The response time of a photodiode together with its outputs circuit depends mainly on the following three factors

1. The transit time of the photocarriers in the depletion region.
2. The diffusion time of the photocarriers generated outside the depletion region.
3. The RC time constant of the photodiode and its associated circuit.

The response speed of a photodiode is fundamentally limited by the time it takes photo-generated carriers to travel across the depletion region. This transit time depends on the carrier drift velocity and the depletion layer width.

The diffusion processes are slow compared with the drift of carriers in the high-field region. Therefore, to have a high-speed photodiode, the photo-carriers should be generated in the depletion region or so close to it, because the diffusion times are less than or equal to the carrier drift times. The effect of long diffusion times can be seen by considering the photodiode response time. The rise time is typically measured from the 10 to the 90 percent points of the leading edge of the output pulse. For fully depleted photodiodes the rise time and fall time are generally the same. The fast carriers allow the device output to rise to 50 percent of its maximum value in approximately 1 ns, but the slow carriers cause a relatively long delay before output reaches its maximum value.

If the depletion layer were 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 region thus tend to show distinct slow and fast-response components.

3- DETECTOR TYPES: -

1- Photoconductors: -

Photoconductors are one of the earliest types photodetector. Their basic principle of detection is the increase in the conductivity of a semiconductor due to the absorption of light. By illuminating the detector chip, phtons with sufficient ionizing energy excite electrons into the conduction band in n-type semiconductors, or generate holes in the valent band of p-type semiconductors. In either case, the incident light changes the number of carriers in the detector chip and reduces the resistance of the detector, which increases the voltage across the load resistor. Fig (1-1) shows a cross section of a photoconductor detector using the thin-film and recent photolithographic techniques to give interdigitated ohmic contacts. Other variations of these structures are possible. However, their basic operation remains the same. On light absorption, the generation of these carriers depends on the wavelength

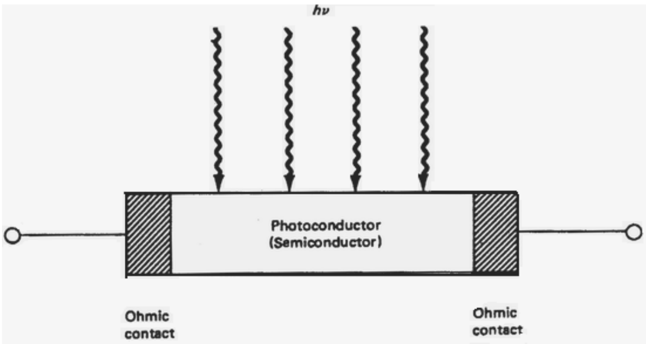


Fig (1-1) Cross section of photoconductor photodiode

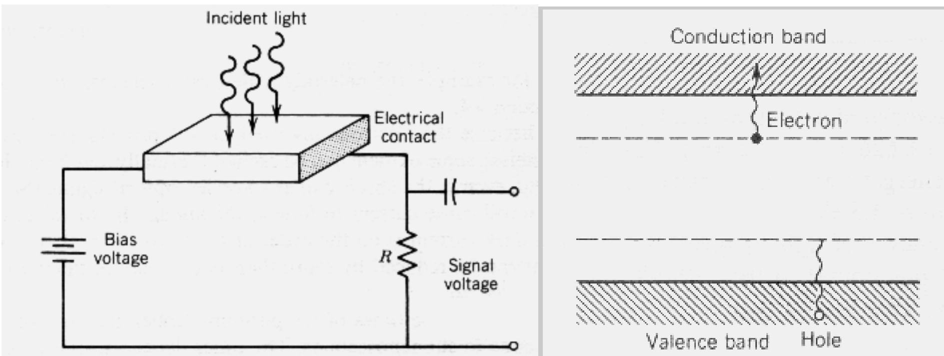


Fig (1-2) the two processes involved in photodetection with a photoconductor

of the light, the forbidden energy gap E_g of the intrinsic semiconductor, and the energy levels of the impurities, E_d and E_A ,in the extrinsic semiconductor.

For low –level optical detection, which is necessary in optical communications, the photoconductors are not as suitable as p-n junction photodiodes in the desired wave length range 0.8 to 1.4 micrometer because the thermal noise predominates at low-level detection, which makes the signal to noise ratio of the photodiodes much higher than that of the photoconductors. However at high-level detection the thermal noise can be neglected, and S/N of photodiodes and photoconductors are comparable. The photoconductor is a very broad bandwidth device, i.e., its detection efficiency beyond the long wavelength limit for a given semiconductor materials remain fairly constant at high-level detection of light. In the wavelength region above 3 micrometer the photoconductors are used extensively. No satisfactory alternatives have been found yet for this long wavelength range, although the recent work with small Schotty barrier heights of silicon appears promising. In summary, photoconductor detectors are not suitable for optical communication in the wavelength range 0.8 to 1.4 micrometers. However, for longer wavelengths, photoconductors are used extensively.

2- PHOTOMULTIPLIERS: -

Figure (2-1) is a schematic of the so-called head-on type photomultiplier tube, which consists essentially of the cathode, the electron multiplier section, and the anode. The cathode consists of materials with a low surface work function, which is the energy needed to eject the electron from the material. Typically, these materials are made of compounds of silver- oxygen-cesium and antimony-cesium. Fig (2-2) is schematic of the energy required in the photoemission process. The electron in the conduction band (where the electron is free) can ejected from the surface into the vacuum if it can overcome the work function W. an incident light at frequency *v*, with quantized

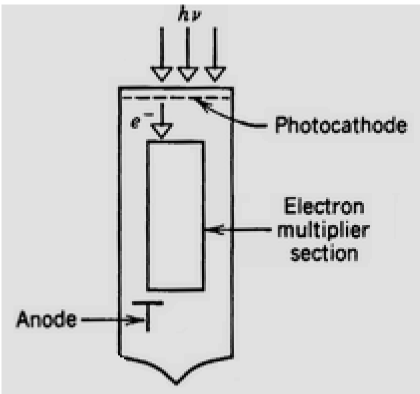


Fig (2-1) Schematic of a head-on-type photomultiplier tube

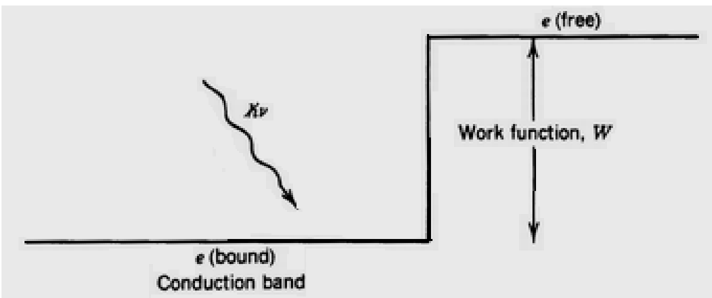


Fig (2-2) the photoemission process

energy unit h*v*, will be able to eject the electron if h*v*>w. typically, the work functions W for these cathode materials are on the order of 1.5 eV, corresponding to the optical wavelength λ in the ultraviolet (0.1 μm) to the infrared (1.1 μm) region. The spectral responses of some commercial phototubes are shown in figure (2-3).

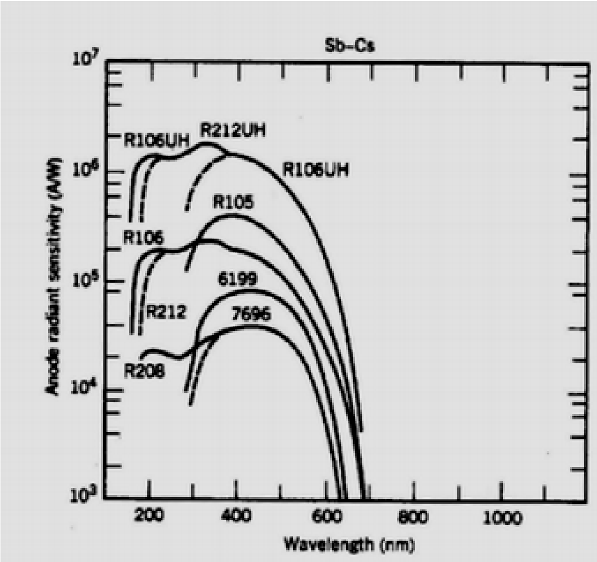


Fig (2-3) the typical spectral response of a photomultiplier tube with Sb-Cs as the cathode material

The electron that is ejected from the photocathode is accelerated to the anode via the electron multiplier, which consists essentially of a series of dynodes at a dc voltage bias of about 100eV. This kinetic energy enables the electron to cause secondary emission from the dynode. As the electron and the secondary electrons are accelerated down the chain, the process of electron multiplication is repeated, leading finally to substantial current being collected at the anode. Typically, one electron creates on the order of about five secondary electrons. If there are ten dynodes, one electron ejected from the cathode will give rise to 5^{10} electrons at the anode, figure (3-4) shows this mechanism for three type of photomultiplier.

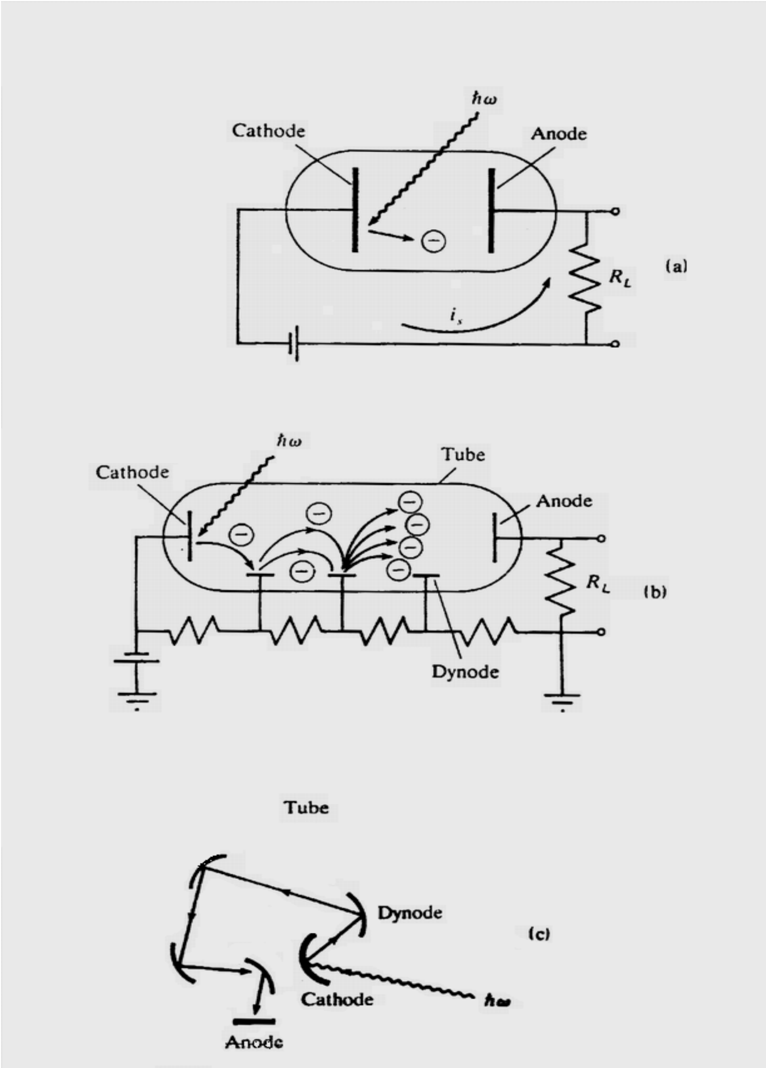
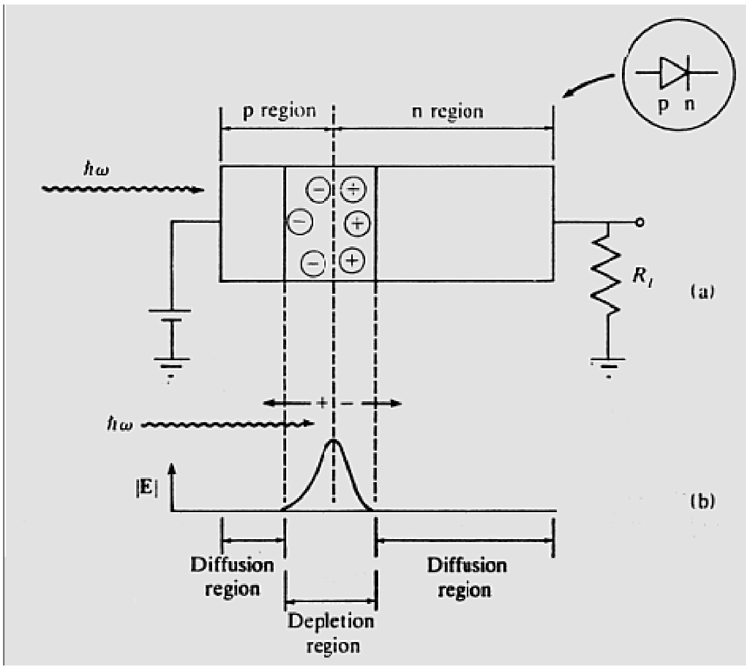


Fig (2-4) (a) Vacuum photodiode (b) photomultiplier
(c) Photomultiplier with focusing mechanism

Photomultiplier tubes are square-law detector, which means that the response from the photomultiplier tube is proportional to the square of modulus of the electric field from the incident light. This square-law response is also characteristic of photoconductors and photodiodes.

3- P-N PHOTODIODE:

The simple p-n diode is illustrated in fig (3-1). The diode junction is reverse-biased, causing mobile holes (electrons) from the p (n) region toward the n (p) region leaves behind the immobile negative acceptor ions (positive donor ions), which, in turn, establish an electric field distribution in the vicinity of the junction called depletion region, as shown in fig (3-1-b). Because there are no free charges, the resistance in this region is high, so that the voltage drop across the diode mostly occurs across the junction. When an incident photon is absorbed in the depletion region after passing through the p-layer, it raises an electron from the valance to the conduction band the electron is now free to move, and a hole is left in the a valance band. In this way, free charge carrier pairs, commonly called photocurrents, are created by photon absorption. These moving carriers then cause current flow through the external circuit.



fig(3-1) (a) p-n diode . (b) Electric field distribution across the diode

In order to generate the electron-hole pair, the incident photon must have energy larger than that of the band gap E_g between the valance and the conduction bands, that is, $h\ w_0 > E_g$. In terms of the cutoff wavelength λ_c, we have

$$\lambda_c = 1.24 / E_g \qquad (3\text{-}1)$$

With E_g measured in electron volts, the cutoff wavelength is about 1.06µm for silicon and 1.6 µm for germanium, where their band-gap energies are 1.1 and .67 eV, respectively. Just as in the case of the external photoelectric effect, not all wavelengths lower than λc can generate photocarrier, as the absorption of photons in the p and n regions is increased at the shorter wavelengths. After photocarrier are generated in the p and n region, most of the free carriers will diffused randomly through the diode and recombine before reaching the depletion junction. The quantum efficiency η for the semiconductor junction diode can then be defined as the number of electron-hole pairs per incident photon.

Two main factors limit the response time of a photodiode:
1-the transit time of the photocarriers through the depletion region
2-the diffusion time of photocarriers (generated in the depletion region) through the diffusion region.
Carrier diffusion is inherently a slow process. In order to have a high-speed photodiode, the carriers should be generated in the depletion region in the high field intensity area or close to it so that the diffusion times are less than the carrier transit times. This can be accomplished by increasing the bias voltage, but practical constraints limits the applied bias voltage.

4-THE PIN PHOTODETECTOR

Another method is to add an intrinsic region between the p and n regions, as shown in fig (4-1-a), where we have a popular PIN diode structure. Fig (4-1-b) shows its corresponding electric field intensity E as a function of distance. It can be shown that the electric field intensity in the intrinsic region is high, when a photon is injected into the intrinsic region, an electron –hole pair is created. The hole drifts toward the p region and the electron towards the n region, thereby generating a current flow in the external circuit. The use of a wide intrinsic layer improves the quantum efficiency because the incident photons will be absorbed in it rather than in the thin depletion region as in the p-n diode, also, it lowers the junction capacitance $C_j = \varepsilon A / W$, where ε and W denote the permittivity and the width of the intrinsic layer, respectively, and A is the area of the junction.

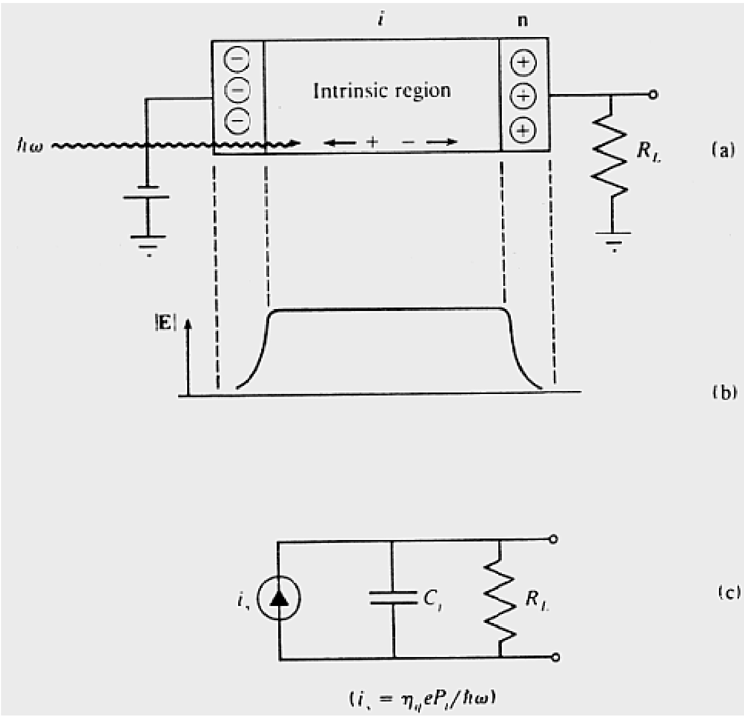


fig (4-1) (a)PIN diode , (b) electric field distribution
(c) Equivalent circuit of a PIN diode

Just as the speed of response in p-n diodes is limited by the transit time of the photocarriers through the depletion region, the speed of response in PIN diodes is limited by the transit time of the carriers through the intrinsic region. Increasing the bias voltage can reduce the transit time, as the velocity of the free charge carriers is proportional to the magnitude of the bias voltage.

5- P-N junction avalanche photodiode: -

To achieve internal gain for junction diodes, that is, to devise a means for generating more than one electron-hole pair for each detected photon, one uses the avalanche effect. Figure (5-1-a) shows the structure of an avalanche photodiode (APD). The p^+ and n^+ layers are highly doped. The p^- region is lightly doped and nearly intrinsic. When photons are absorbed in this region, electron-hole pairs are created. As in the PIN diode, the holes and electrons drift towards the p^+ and n^+

regions, respectively. However, before the electron reaches the n^+ region, it passes through a p-type multiplying region. In this region the electron is accelerated by the high E field as shown in figure (5-1.b). If the electron undergoes sufficient acceleration in the region, new electron-hole pairs are created by the collision-ionization process. These newly created electron-hole pairs themselves generate more electro-hole pairs, thus creating the so-called avalanche multiplication .in this way the number of electron-hole pairs created may be multiplied by a factor of 1000 over the traditional PIN photodiodes.

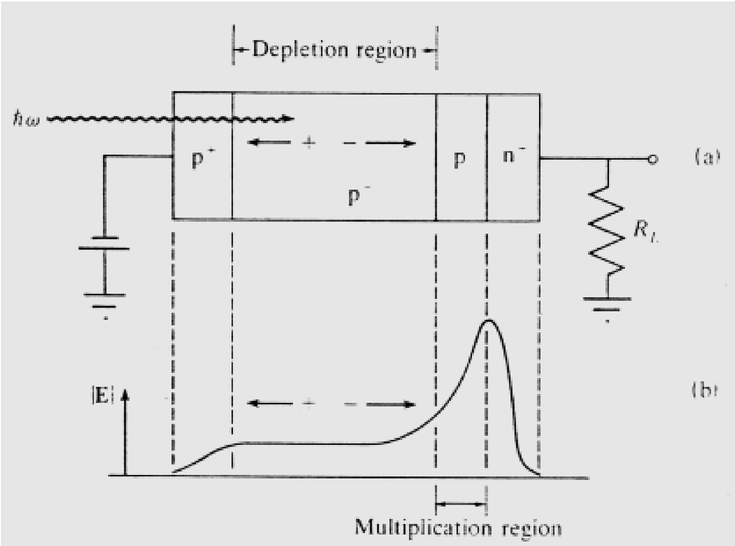


Fig (5-1) Avalanche photodiode: (a) junction configuration
(b) Electric field distribution

The ionization coefficient of electron and holes are in general not equal, and they also depend on the electric field. These ionization coefficients are $r_n(E)$ for electrons and $r_p(E)$ for holes. The values of $r_n(E)$ and $r_p(E)$ depend not only on the material but also on the geometry of the photodiode because of the electric field dependence. There are two special cases: -

1- negligible ionization rate: - if the condition $r_n=0$ or $r_p=0$, equivalent to either $r_n>>r_p$ or $r_p>>r_n$, can be achieved in a semiconductor material because of its intrinsic properties and the geometry used, the possibility of obtaining the highest performance in an avalanche diode is enhanced.

2- Equal ionization rates: - the condition $r_n=r_p$ is the worst case for performance in an avalanche diode. In this case, even though the gain or multiplication can be large, the statistical variations in the impact ionization process can produce large fluctuations in the gain and consequently considerable excess noise.

In construction, an avalanche photodiode is similar to a p-n diode having a mesa structure or a guard ring. Figure (5-2) below shows cross section of various types of structures of avalanche photodiodes. Also shown are the electric fields and the multiplication factors for each structure. The operating voltages of avalanche diode are higher than those for p-n or PIN diodes, so that the breakdown fields are reached.

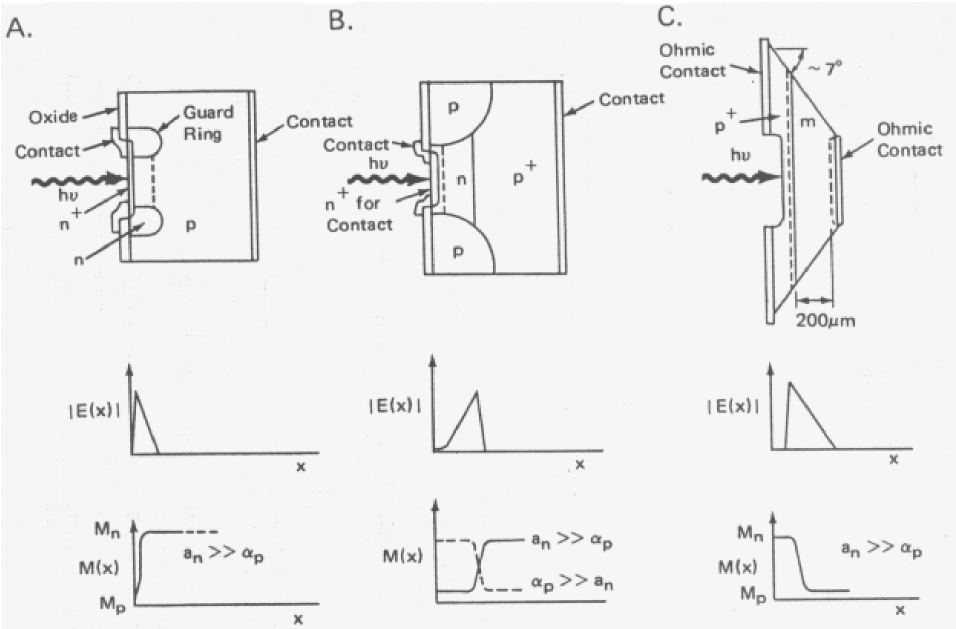


Fig (5-2) Various avalanche photodiode devices (a) n^+-p guard ring structure (b) inverted, no guard ring, n^+-p structure (c) beveled-mesa or contoured-surface structure (d) n^+-p-pi-p reach-through structure

The carriers multiply by impact ionization, and both electrons and holes undergo multiplication. The multiplication factor *M* can be written

$$M = 1 / (1 - [(V - I R)/ V_B]^n)$$

Where *V* is the applied voltage, V_B the breakdown (depends on the geometry of the diffused junction, the receptivity, and the thickness of the active semiconductor layers), I the total output current, *R* the total effective series resistance (depends on area, thickness, and receptivity), and n a constant (depends on the semiconductor used, the doping profile of the diffused junction and the wavelength of light being detected).

In the long-wavelength region (1 – 1.4 micrometer), the quantum efficiencies of Si photodiodes drop rapidly, because of the rapid decrease in the absorption coefficient of light in Si in this wavelength region. To increase the quantum efficiency of Si APDs in this range, side illumination of the diodes and trapping of the light in the diode by near total internal reflection are used. Figure (5-3) illustrates these two approaches. Fig (a) shows that the incident light enters the edge in a plane parallel to the junction and perpendicular to the electric field. By making the junction longer, the path length of the light to be detected is increased. This enhances the probability of absorption within the photodiode and hence increases the quantum efficiency. The same object is also achieved by trapping the light in a thin-film structure by near-total internal reflection, see fig (B). Light enters thought the junction in a conventional manner, but with appropriate back and front reflecting contacts the light is multiplied reflected within the depletion layer. Thus, the path length is increased, giving improved quantum efficiency.

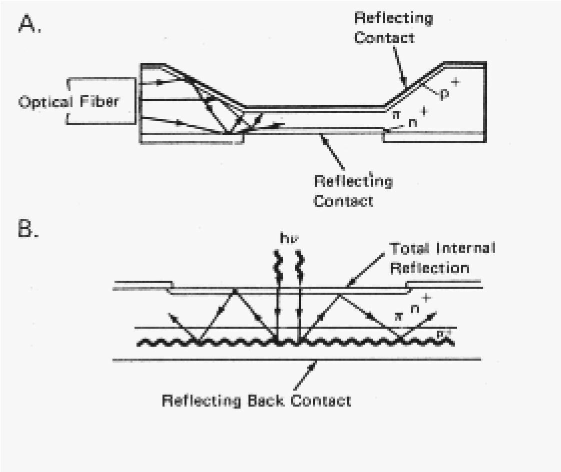


Fig (5-3) two proposed structure for increasing the long-wavelength quantum efficiency of high-speed Si photodiode (a) edge-illuminated structure (b) multiple-reflection structure

Note that APDs require a circuit for the high reverse-bias voltage that ranges from tens to hundreds of volts, whereas in PIN diode circuit a few volts of reverse-bias are usually sufficient. Hence, the APD gain is preferable in most laboratory systems however, the APD gain is needed when the system is loss-limited, which may occur for long-distance fiber optic links. Also, an arbitrarily large value of multiplication factor is avoided, since the avalanche multiplication also contributes additional noise. Under high reverse bias voltage, electron-hole pairs are not only created by the absorbed photons, but are also created by thermal processes. Thus thermal runway is distinct possibility to high values of M.

6 - Electroabsorption avalanche photodiode: -

Electroabsorption avalanche photodiode (EAPD) are avalanche photodiodes made from a direct-gap semiconductor material like GaAs having low carrier concentration ($<10^{15}$ cm^{-3}) In these diodes, the responsively and quantum efficiency are high at wavelengths close to and beyond the absorption edge in GaAs, and the avalanche gain at these long wavelength is much higher than the gain at short wavelengths. This improved performance of EAPDs is due to the Franz-Keldysh effect, i.e., shift of the absorption edge due to electric field. Qualitatively, the highly asymmetric values of electron (r_n) and hole (r_p) ionization coefficients for GaAs ($r_p/r_n >> 1$) with low carrier concentration ($<10^{15}$ cm^{-3}), gives rise to the enhanced spectral response at long wavelengths.

4- PERFORMANCE

The performance characteristics of photodetectors can be described by noise, sensitivity, bandwidth, and dark current. Often, other performance parameters are used to evaluate the detector behavior, but usually they are of secondary importance. Detectors generally present fewer problems with respect to system performance than most other system components.

Most optical detectors offer reasonably good performance at 0.85 µm, but at larger wavelengths, such as at 1.06 and 1.27 µm, their performance is significantly degraded. Tables 1 and 2 summarize the characteristics of typical devices.

One of the most critical criteria in determining the usefulness of a detector is its noise characteristic. The presence of noise is one of the major limitations of system performance. For example, the maximum length of fibers dictated by signal pulse degradation is affected in part by detector noise. Consequently, it is generally desirable to avoid system operation in the noise-limited mode. The major detector types display a noise equivalent power in the range 10^{-14} to 10^{-13} W/Hz$^{1/2}$. The guard ring and reach-through devices offer better performance. High-speed quantum efficiencies typically range from 0.25 to 0.95 (including tail). The differences are due mainly to variations in depletion region width and/or to a diffusion tail affecting equivalent quantum efficiency at high speed. Bandwidth typically exceeds 100 to 200 MHz and is highest for avalanche devices.

TABLE 1Characteristics of State-of-the-Art Optical Detectors Suitable for Optical Communications

	Photoconductive detectors			Avalanche detectors	
Characteristic	PN diode	PIN diode (no GR*)	PIN diode (with GR)	APD (with GR)	Reach-through
Sensitive area (mm^2)	10-100	10-50	10-50	1-10	1-10
Reverse bias (V)	20-150	10-50	50-150	100-200	200-500
Capacitance (pF)	1-5	5-10	1-5	5-10	1-5
Noise, NEP *(10^{-14} W/Hz$^{1/2}$)*	10-15	10-20	5-10	1-2	0.5-1.0
Dark current(nA)	10-30	20-50	5-20	1-5 (s) 0.05-l(b)	50-200 (s) 0.05-0.2 (b)
Quantum efficiency	0.80-0.90	0.85-0.95	0.85-0.95	0.30-0.50	0.80-0.90
Bandwidth (MHz)	200-300	50-75	75-100	500-1000	100-200

TABLE 2 Advantages and Disadvantages of Principal Classes of Optical Detectors Useful for Fiber Optics Communications

Photodetector	**Advantages**	**Disadvantages**
p-n diode	Simple structure High quantum efficiency Moderately high bandwidth	High noise equivalent power Relatively high dark current Quantum efficiency and bandwidth affected by slow tail
PIN diode without guard ring	Low bias voltage High quantum efficiency	High noise equivalent power High dark current Low bandwidth High capacitance Large sensitive area
PIN diode with guard ring	Reduced noise equivalent power Low dark current High quantum efficiency	More complex structure Large sensitive area Low bandwidth High capacitance
Avalanche photodiode with guard ring	Low dark current Low noise equivalent power High bandwidth Small sensitive area	Low quantum efficiency High bias voltage High capacitance Quantum efficiency and bandwidth affected by slow tail Temperature sensitivity requires temperature compensating network
Reach-through Avalanche Photodiode	Low dark current Very low noise equivalent power Medium bandwidth High quantum efficiency Small sensitive area	Very high bias voltage Temperature sensitivity requires temperature-compensating network

The light-sensitive areas of optical detectors are comparable to typical fiber bundle cross-sectional areas, but they are significantly larger than those of single fiber core areas. Whereas the maximum cross-sectional area of a fiber core of 100 μm diameter is about 3 x 10^{-2} mm^2 and thus represents the maximum core area normally encountered for a single fiber, the sensitive area of most detectors is typically two to three orders of magnitude larger. As a result, the detection of information from fiber bundles requires the physical separation of the fibers during detection so that each fiber can transmit its data to its own detector. This presents a considerable inconvenience. Also, the fiber-detector area mismatch indicates a poor utilization of the optical power. Substantial interface losses are usually encountered with both PIN and APD detectors because of the fiber-detector separation caused by the conventional packaging methods and the divergence of the emission from the fiber ends. Very close fiber-detector spacing is required in most cases to reduce these coupling losses to a minimum. Considerations similar to those made for the source-fiber connections apply. Typically, coupling losses at the fiber-detector interface range from 0.5 to 1.5 dB per fiber.

Most optical detectors suffer from two major difficulties: the slow-tail frequency response of nonavalanching (PIN) devices and the temperature dependence of the avalanche process of avalanching (APD) devices. The speed of optical detectors is largely a function of the detector capacitance, which is composed of the device and package contributions. The device capacitance depends upon the width of the depletion layer and is therefore a function of the impurity concentration and the applied voltage. Since a large operating voltage affects a wide depletion layer and hence a smaller capacitance compared to an otherwise identical device operated at low voltage, APDs usually have a higher frequency response than PINs. The slow-tail response is encountered in nondepleted devices. It is a temporal response component, which lags the main component and is due to photon absorption in the nondepleted bulk. In a typical nondepleted device, up to 50% of the pulse response may be due to the slow tail. It is responsible for intersymbol interference, low quantum efficiency, and other performance degradation.

Typically, the avalanche process has a temperature coefficient of 0.2 V/°C for the guard ring structure and of 1.8 V/°C for the reach-through structure. Therefore, the avalanche voltage is a sensitive function of temperature, so that avalanche photodetectors require the addition of temperature-compensating circuitry.

The quantum efficiency of a PIN detector can be maximized if the width of the active region is several times the light penetration depth within the semiconductor. On the other hand, the frequency response of the device decreases with the width of the active region. Hence, bandwidth and efficiency normally involve a trade-off. In order to obtain a detector with both high sensitivity and fast response, the paths for penetrating photons and generated carriers must be different. One way to achieve this is to illuminate the intrinsic layer parallel to the junction plane rather than from the top. Higher efficiency is achieved if the thick substrate of the device is removed and only a very thin contact layer is left, whereby the metalized back contact serves as a reflector; in this case, the light path is twice that of the generated carriers. When there is only a small opening in the top contact through which the light can penetrate under a large angle, the optical power is reflected up and down between two mirrors and completely absorbed within the semiconductor material. In practice, such a structure has a relatively high quantum efficiency (in excess of about 0.5 if only back-side reflection is used) and a fast response time (about 0.1 ns, corresponding to 10 GHz). Approximately 40% of the response time is caused by delay in the rather thick contact layers. Enhanced performance can be expected by the use of improved antireflection coatings and of back contact gratings to allow multi-reflection of the light within the detector.

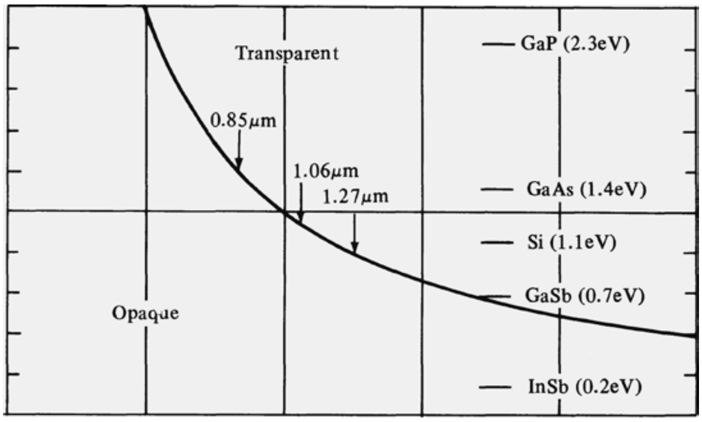
Silicon avalanche photodiodes have a serious efficiency-frequency trade-off. This is a consequence of the indirect energy gap of silicon and its relatively low value, which results in opacity of the material. The efficiency-frequency product ηf of silicon (which has an optical absorption coefficient of 10 cm^{-1} at 1.06 µm) is about 40 MHz; it is assumed that the frequency is taken at the 3 dB point. This relatively small ηf for silicon can be contrasted to that of direct-gap compound semiconductors, which generally have a higher efficiency-frequency product. They are frequently transparent and hence have a small absorption coefficient, and they are characterized by high carrier mobility.

Generally, semiconductors whose energy gap E_G is larger than the photon energy E_{ph} are transparent, whereas materials whose energy gap is smaller than the light energy are opaque. Note that E_{ph} is wavelength dependent. This situation has implications for the usefulness of semiconductors as efficient optical detectors, since it is desirable to use opaque and hence light-absorbing materials in the active device region and transparent materials in the surrounding regions in order to achieve deep photon penetration down to the active layer. The relationship between photon energy E_{ph} and photon wavelength (wavelength of light) is given by:

$$E_{ph} = h\upsilon = hc/\lambda \qquad (4)$$

Where $h = 4.14 * 10^{-15}$ eV s and $c == 3 * 10^{10}$ cm/s. This is illustrated in Figure 1. Thus, photon energy is inversely proportional to wavelength and hence at larger wavelength, such as $\lambda = 1.27$ µm, the photons possess about 50% less energy than at X = 0.85 µm to penetrate the semiconductor material. For reference, the energy gaps of a few applicable semiconductors are as follows: InSb, 0.2 eV; Ge, 0.7 eV; GaSb, 0.7 eV; Si, 1.1 eV; GaAs, 1.4 eV; CdS, 2.6 eV; and ZnS, 3.6 eV.

Photon Energy, E_{ph} (eV)



Wavelength, λ (µm)

Figure 1: Relationship between photon energy and light wavelength, indicating the transition from opacity to transparency as the wavelength or the material energy gap increases.

TABLE 3 Properties of High-Sensitivity Photodetector

Material	Energy gap (eV)	Optical Transmission	
		at 0.85 µm	at 1.06 µm
n^+-GaAs	1.4	Opaque	Transparent
n^+-$GaAs_{1-y}Sb_y$	>1.2	Opaque	Transparent
n^--$GaAs_{1-x}Sb_x$	<1.1	Opaque	Opaque
n^--$GaAs_{1-z}Sb_z$	>1.2	Opaque	Transparent

5- NOISE LIMITATIONS

One of the most stringent requirements on an optical detector is the reduction of the noise level. This is particularly important because the detector itself is normally the principal noise contributor in a fiber optics communications system. Noise presents one of the most severe systems limitations; it affects the maximum fiber length or the maximum allowable distance between repeaters. Therefore, it is of major interest in economic considerations.

The treatment of detector noise and its effect on the operational limits of an optical system centers around an analysis of the ratio of signal power to noise power (S/N ratio). Efforts to improve system performance thus are directed toward an increase of the S/N ratio as long as this is economically justifiable. The signal-to-noise ratio is a function of the allowed error probability or bit error rate and involves a complementary error function (erfc). The bit error rate or probability of error (ε) for a binary (on-off), i.e., digital, scheme is related to the signal-to-noise ratio by

$$\varepsilon = 1/2\ \mathrm{erfc}[(S/N)^{1/2}/(2)^{1/2}] = 0.4\ (S/N)^{-1/2}\ e^{(S/N)1/2} \qquad \text{for } S/N > 10 \qquad (5)$$

This is shown graphically in Figure 2. In typical systems a bit error rate of 10^{-9}, corresponding to S/N of about 36 dB, is desirable. The need for high S/N

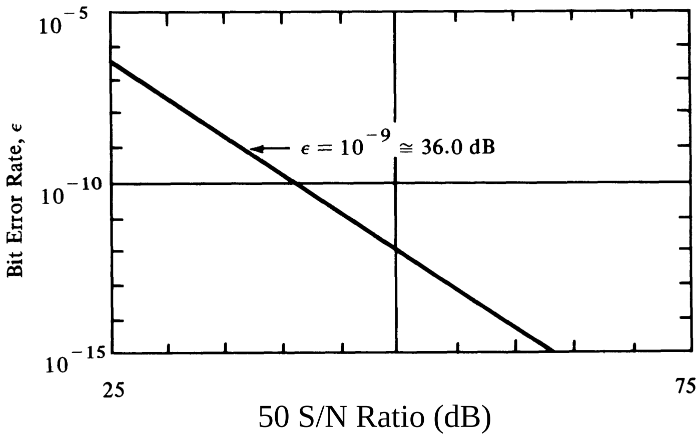


Figure 2 Relationship between error rate and signal-to-noise ratio.

In order to reduce the error probability is evident because of the strong relationship. For example, a reduction in the bit error rate from 10^{-6} to 10^{-9} requires an increase in S/N from about 17 dB to 36 dB.

The signal-to-noise ratio is a function of several noise-generating mechanisms. The signal power depends upon the source power, the fiber input and output coupling efficiency, and the fiber attenuation. The noise power depends upon the contributions of the general expression for the signal-to-noise ratio; we can distinguish two major cases, as follows:

Absence of background light. Depending upon whether the detector is a unity-gain (PIN) or a high-gain (APD) device, there are two different situations: In a unity-gain detector, thermal noise dominates and the signal-to-noise ratio is given by

$$S/N = (\alpha P_0)^2 R_L/4kTB \qquad (6)$$

In a high-gain detector, shot noise dominates and the signal-to-noise ratio is given by

$$S/N = (\alpha P_0)/qB \qquad (7)$$

Presence of background light. In this case, the detector gain and type are arbitrary; background noise dominates and the signal-to-noise ratio is given by

$$S/N = (\alpha P_0)RL/ \ 2qB(l + P_b/P) \qquad (8)$$

In these expressions, *a* is the fiber attenuation, η is the detector quantum efficiency, m is the modulation index, P_0 is the average optical power at the detector, P_b is the average optical power of the background, and *B* is the bandwidth of the detection system. In most applications where the fibers are coated by an opaque material the case for background light is negligible. In the case of dominant background noise, it is assumed to be much larger than the optical power, $P_b >> P_0$.

The system operation thus may be limited by either of three types of noise. These are discussed below.

a-Quantum Noise

In this case, noise is the result of fluctuations in the average signal current according to

$$S/N = \eta m^2 P_0/4BFE_{ph} \qquad (9)$$

In this equation F is the noise increase due to detector current gain (applicable to APDs only), and Eph is the optical energy received by the detector (on the order of 1 eV, depending upon the wavelength). Quantum noise represents the inherent limit in a system. In practice, this lower noise limit is usually not achievable, although it may be approached. Theoretically, S/N can be maximized by an increase in signal power and wavelength and by a decrease in detector bandwidth and amplifier gain. In practice, however, not all of these objectives are attainable or necessarily desirable because of potential trade-offs. An overall optimization normally leads to a system condition in which quantum noise is not minimized. In spite of this, quantum noise is usually secondary to the other two noise contributions. The resultant maximum pulse rate applicable to the quantum noise-limited case is approximately

$$R_{max} = A_q e^{-\alpha L} \qquad (10)$$

Where A_q is a proportionality factor.

b-Thermal Noise

In the absence of internal detector gain (such as in the case of PIN diodes), this noise contribution is mainly due to thermal fluctuations or shot noise:

$$S/N = (\eta m P_0)^2/(8(E_{ph}/q)^2 kT_e B/R_e) \qquad (11)$$

The effective noise temperature T_e accounts for thermal and amplifier noise, and the equivalent load resistance R_e depends upon the detector geometry and the amplifier impedance. The terms *q* and *k* are electron charge and Boltzmann's constant, respectively. In the case of thermal noise, S/N is proportional to $(\eta P_0)^2$, whereas in the case of quantum noise, S/N is proportional to ηP_0. Both T_e and R_e depend on device and amplifier characteristics. If the amplifier is noiseless and has zero input admittance, then T_e and R_e are the physical temperature and the resistance of the load, respectively; if the amplifier contributes noise, then T_e is approximately the product of the amplifier noise figure and the ambient temperature. Based on the thermal noise model, the maximum data rate that can theoretically be expected is given by

$$R_{max} = A_t e^{-2\alpha L} \qquad (12)$$

Where A_t is a proportionality factor. Note the factor 2 in the exponent, in contrast to the factor 1 for the quantum noise model.

c-Shot Noise

In the presence of internal detector gain, given by the term G and found in avalanche photodiodes, shot noise contributes to the detector noise. It is minimized when the shot noise is amplified to the level of the thermal noise. In this case, S/N is equal to that in the thermal noise case multiplied by the factor $G_{opt}/(2)^{1/2}$. If the detector gain exceeds the optimum, the detector sensitivity diminishes because of excess noise generated in the carrier multiplication process. Similar to the data rate limitation caused by thermal noise, the maximum data rate possible in the case of optimum detector internal gain is

$$R_{max} = A_g e^{-2\alpha L} \qquad (13)$$

Where the proportionality factor $A_g = A_t\, G_{opt}/(2)^{1/2}$. Because the equivalent resistance is composed of the internal resistance of the detector and the load resistance, it is usually inversely proportional to the product of capacitance and maximum bandwidth of the detector circuit. If thermal noise limitation exists, then noise increases with the square of bandwidth. In the case of optimum gain the noise increase is proportional to bandwidth.

Factors Influencing Noise

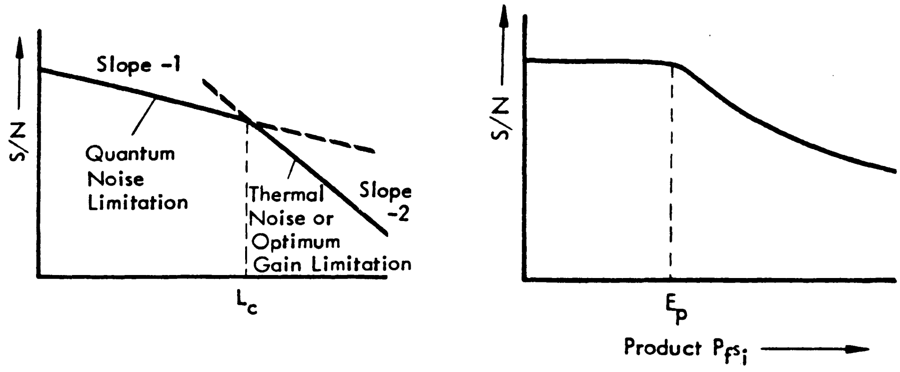
It is desirable to separate the influences on the noise characteristics caused by the optical power from influences that are independent of the optical power. This means that S/N can be expressed

$$S/N = uP_0^2/(P_0 + P_f) \qquad (14)$$

Where u is a factor that includes η, λ, B, and F. The denominator is the sum of a P_0-dependent and a P_0-independent term (P_f); P_f refers to fixed noise sources and excludes all contributions by P_0. For a given average optical power P_0, advantage can be gained by decreasing the pulse width at the expense of bandwidth to ensure that the detector is always limited by optimum gain; hence, bandwidth capability can be exchanged for optical power.

In the discussion above we distinguished between two cases. If $P_0 >> P_f$, then the S/N ratio varies exponentially with fiber length, according to S/N $\sim e^{-\alpha L}$; if $P_0 << P_f$, then S/N $\sim e^{-2\alpha L}$. Thus, at a critical fiber length L_c the slope of a In S/N-versus-L plot exhibits a change, meaning that at long fiber lengths the signal-to-noise ratio decreases faster with distance than at short fiber lengths. In other words, for long cables the magnitude of the slope is twice its value for short cables. This is illustrated schematically in Figure 3A.

This analysis indicates a P_0 dependence of S/N in the case of quantum noise and a P_0^2 dependence in the case of thermal noise and optimum gain. This difference is of economic importance because it is related to the maximum distance between repeaters and the required power output of the source.



A **B**

Figure 3 schematic illustrations of the variation of the signal-to-noise ratio with fiber length and product of pulse width and fixed-noise source energy.

The signal-to-noise ratio can be described in terms of the energy received by the light pulse, $E_p = P_0 S_i$, under the assumption that the pulse width at the source, S_λ, has deteriorated to a value at the detector, 5, whereby the bandwidth is defined as the inverse of S_i, (so that $B = 1/S_i$,):

$S/N = uE_p^2/(E_p + P_f S_i)$ (15)

It is evident that for a given pulse energy E_p the signal-to-noise ratio can be increased by reducing the pulse width S_i. Thus, a laser source of small spectral width is more advantageous to use for high S/N ratio than an LED source. This assumes that signal noise has been limited by adjusting S_i, such that $P_f S_i << E_p$. In this case, the pulse width can be decreased while the pulse energy remains constant. As Figure 3B indicates, decreasing the $P_f S_i$ product much below E_p does not result in a significant S/N enhancement. There is a seeming conflict with the requirement of a minimized bandwidth to reduce noise. It can be resolved by considering the fact that a smaller pulse width results in both a reduced receiver integration time and a smaller number of photon-generated electrons due to fixed noise sources, resulting in higher sensitivity.

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