Unit: III

Photodetectors: PIN photodetector, avalanche photodiodes, photodetector noise, detector response time, avalanche multiplication noise. Signal degradation in optical fibers: Attenuation: units, absorption, scattering losses, bending losses, core and cladding losses. Signal distortion in fibers: overview of distortion origins, modal delay, factors contributing to delay, group delay, material dispersion, waveguide dispersion, polarization-mode dispersion. Characteristics of single mode fibers: refractive index profiles, cut-off wavelength, dispersion calculations, mode field diameter, bending loss calculation.

Photo detector-: Is first element sense the luminescent power falling upon it and convert variation of this optical power into a corresponding varying electric current.

Photodiode is almost exclusively for fiber optic systems because of its small size, suitable material, high sensitivity and fast response time. The two types of photodiode used are PIN photo detector and avalanche photodetector (APD).

3.1 PIN PHOTO DIODE

The device structure as shown in Fig. 3.1 consist of P and N regions separated by very lightly N-doped intrinsic I 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. That is in intrinsic region carrier concentration is very small as compared to the P and N regions.

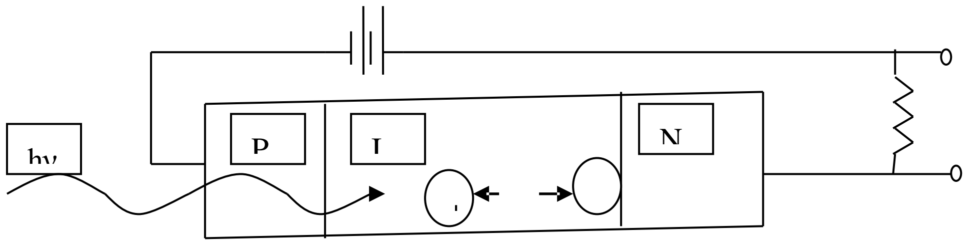

Fig. 3.1 PIN Photodiode

When a 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 valence band to the conduction band, This process generates mobile electron-hole pairs. The electric field present in the depletion region causes the carriers to separate and be collected across the reverse biased junction. This gives rise to a current flow in an external circuit, with one electrons flowing for every carrier pair generated, This current is known as the Photo current.

The performance of a photodiode is often characterized by the renponsivity R. This related to the quantum efficiency by

$$R=\frac{I_p}{P_{in}}=\frac{\eta q}{h\nu}$$

This parameter is useful, since it specifies the photocurrent generated per unit optical power. Responsivity is a linear function of optical power. That is photocurrent I_p is proportional to the optical power P_{in}

incident upon the photodetector, so that the responsivity R is constant at a given wavelengths (at a given hv). Note however that the quantum efficiency is not a constant at all wavelengths, since it varies according to photon energy. Consequently, the responsivity is a function of the wavelength and of the photodiode material (since different materials have different band-gap energies). For a given material, as the wavelength of the incident photon becomes longer, the photon energy becomes less than that required to excite an electron from the valence band to conduction band. Responsivity thus falls of rapidly beyond the cutoff wavelength.

3.2 Avalanche Photodiode

Avalanche photodiode (APDs) internally multiply the primary signal photocurrent before it enters the input circuitry of the following amplifier. This increases the receiver sensitivity, since photocurrent is multiplied before encountering the thermal noise associated with the receiver circuit.In order carrier multiplication to take place, the photo generated carriers must traverse a region where a very high electric field is presented. In this high-field region, a photo generated electron or hole can gain enough energy so that it ionizes bound electrons in the valence band upon colliding with them. This carrier multiplication mechanism is known as Impact Ionization.The newly created carriers are also accelerated by the high electric field, thus gaining enough energy to cause further impact ionization. This phenomenon is called avalanche effect.

A commonly used structure for achieving carrier multiplication with very excess noise is the reach –through construction (RAPD). The reach through avalanche photodiode (RAPD) composed of high resistivity P type material deposited as an epitaxial layer on P+ substrate. Then n+ layer is constructed. This configuration is referred to as P+πpn+ reach through structure. The π layer is basically an intrinsic material. When low reverse bias voltage is applied, most of the potential drop is across pn+ junction. The depletion layer widens with increasing bias until a certain voltage is reached at which peak electric field at the pn+ junction is about 5-10 percent below needed to cause avalanche breakdown.

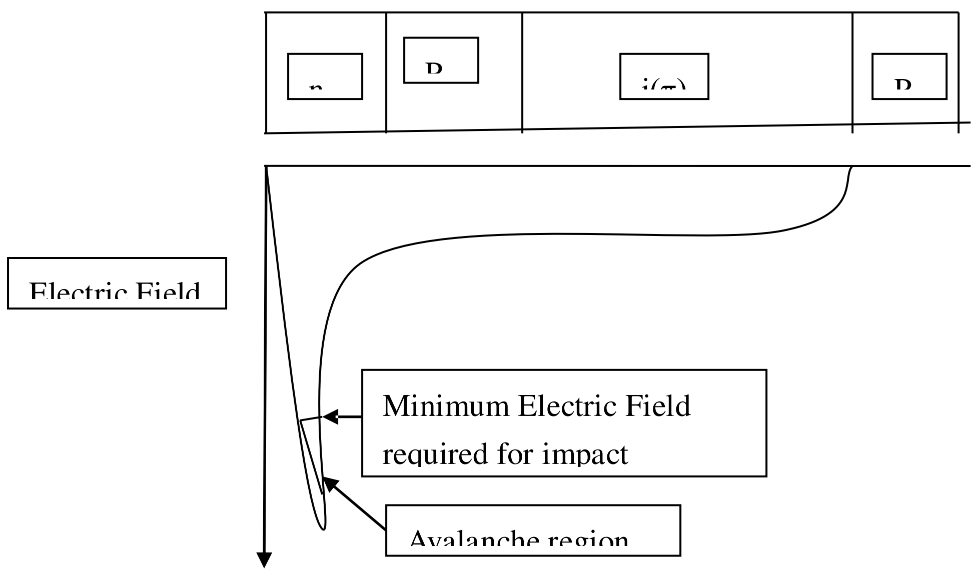

Fig 3.2 Reach through Avalanche structure and the electric fields in the depletion and multiplication region.

Light enters the device through the p+ region and is absorbed in the π material, which act as the collection region for photo generated carriers. Upon being absorbed, photon gives up its energy, thereby creating electron hole pairs which are then separated by electric field in the π region. The photo generated electrons drift through the π region in the pn+ junction, where high electric field exists. It is in this high field region that carrier multiplication takes place. The multiplication M for all carriers generated in the photodiode is defined by

$$M=\frac{I_M}{I_p}$$

Where I_M is the average value of the total multiplied output current I_p is the primary multiplied photocurrent.

3.3 Photo detector Noise

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 circuitry be optimized so that a given signal to noise ratio is maintained. Signal to noise ratio at output is defined by.

$$\frac{S}{N}=\frac{\text{Signal power from photocurrent}}{\text{Photodetector Noise} + \text{amplifier noise power}}$$

Noise Sources

To see different types of noises affecting the signal to noise ratio, let us examine the simple receiver model and its equivalent circuit shown in Fig. 3.3.The photodetector has small resistance R_s a total capacitance C_d consisting of junction capacitance and packaging capacitances and load resistor R_L. The principle noises associated with photodetectors that have no internal gain are 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 statistical nature of the production and collection of the photoelectrons when an optical signal is incident on a photodetector.

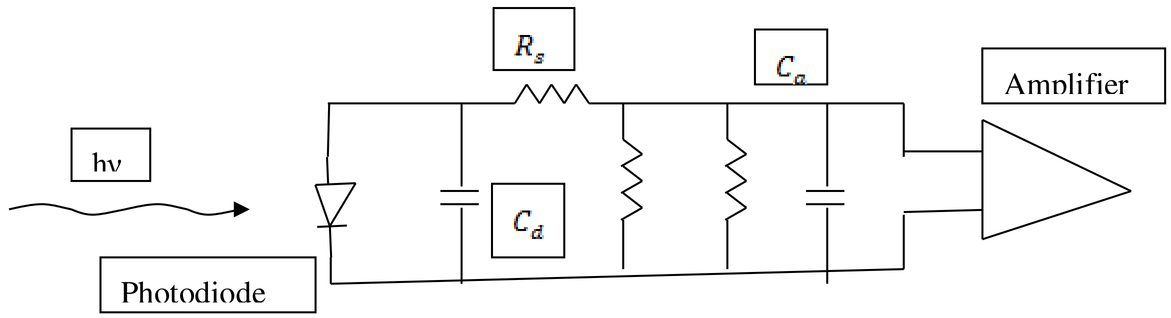

Fig. 3.3 Photo detector Equivalent Circuit

The shot noise current has a mean square value in receiver bandwidth B_e which is proportional to the average value of photocurrent I_p.

$i_{shot}^2=2qI_pB_eM^2F(M)$ -----(1)

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

Photocurrent dark current is the current that continues to flow through the bias circuit of the bulk dark current i_{DB} arises from the electrons or holes which are thermally generated in the pn junction of photodiode.

i_{DB}^2 =2q$I_D B_e M^2$F(M) ----(2)

Where I_D is the primary detector bulk dark current .

Surface dark current is also referred as surface leakage current or simply leakage current. It is dependent on surface defects, cleanliness, bias voltage and surface area. An effective way of reducing surface dark current is through the use of a guard ring structure which shunts surface leakage currents away from the load resistor.

The mean square value of surface dark current is given by

i_{DS}^2 =2q$I_L B_e$ ----(3)

Where I_L is the surface leakage current.

To simplify the analysis of receiver circuitry, we shall assume here that the amplifier input impedance is much greater than the load resistance, so that its thermal noise is much smaller than that of R_L. The photodetector load resistor contribute a mean square thermal (Johnson) noise current.

$i_T^2 = \frac{4 K_B T B_e}{R_L}$ ---(4)

Where K_B is Boltazmann's constant and T is absolute temperature. This noise is reduced by using a load resistor which is large but still consistent with the receiver requirement.

3.4 Response Time

The response time of a photodiode together with output circuit depends on the following factors:

The transit time of the photo carriers in the depletion region

The diffusion of the photocarriers generated outside the depletion region.

The RC Time constant of the photodiode and its associated circuit.

3.5 Attenuation

Signal attenuation also known as fiber loss or signal loss. The basic attenuation mechanisms in a fiber are absorption, scattering and radiative losses of the optical energy.

Absorption: Absorption is caused by three different mechanisms:

Absorption by atomic defects in glass composition.

1. Extrinsic absorption by impurity atoms in the glass material.
2. Intrinsic absorption by the basic constituent atoms of the fiber material.

Atomic defects are imperfections in the atomic structure of the fiber material. Examples are missing molecules, high density clusters of atom groups , oxygen defects in the glass structure.

The dominant absorption factor in silica fibers is the presence of minute quantities of impurities in the fiber material. These impurities include OH- (water) ions that are dissolved in the glass and transition metal ions such as iron, copper, chromium and vanadium.

Intrinsic absorption occurs when the material is in a perfect state with no density variations, impurities , material inhomogeneties and so on. Intrinsic absorption results from electronic absorption bands in the ultraviolet region and from atomic vibration band in the near infrared region.

Scattering Losses:

Scattering losses in glass arises from microscopic variations in the material density, from compositional fluctuations and from structural inhomogeneties or defects occurring during fiber manufacture.Due to variation in the refractive index occurring within the glass over distances that are small compared with the wavelength.these index variations cause a Rayleigh type scattering in the light.

Bending losses:

Radiative losses occur whenever an optical fiber undergoes a bend of finite radius of curvature. Fibers can subject to two types of bends.

i)Macroscopic bends having radii that are large compared to the fiber diameter as shown in Fig. 3.4 ,also known as macrobending losses or simply bending losses. As radius of curvature decreases loss increases exponentially.

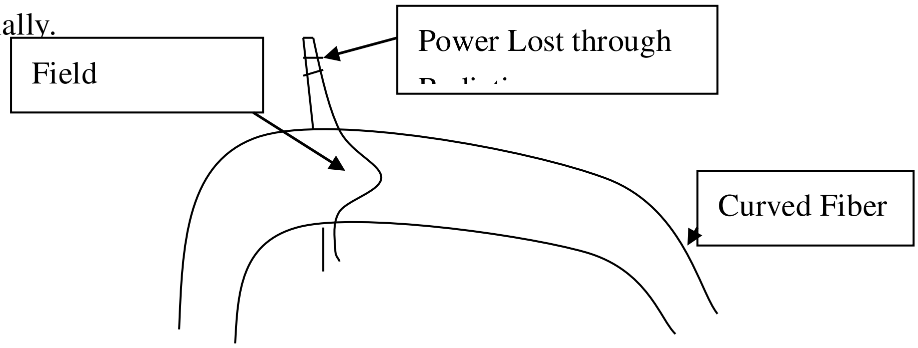

Fig. 3.4 Sketch of Fundamental mode field in curved optical waveguide

ii) Microbends are repetitive small scale fluctuations in the radius of the curvature of the fiber axis. They are caused either by non uniformities in the manufacturing of the fiber or by non uniform lateral pressure created during the cabling of the fiber.

One method of minimizing microbending losses is by extruding a compressible jacket over the fiber. When external forces are applied to this configuration, the jacket will be deformed but fiber will tend to stay relatively straight.

3.6Signal Distortion

An optical signal weakens from attenuation mechanisms and broadens due to distortion effects as it travels along a fiber as shown in Fig.3.5. Signal distortion is consequence of factors such as intermodal delay, intramodal delay, polarization mode dispersion and higher order dispersion effects.

a)Intramodal Dispersion:

Is pulse spreading takes place within a single mode. This spreading arises from the finite spectral emission width of an optical source. This phenomenon is known as group velocity dispersion, since dispersion is a result of the group velocity being a function of the wavelength.

b)Intermodal Dispersion: Appears only in multimode fibers, modal delay is the result of each mode having a different value of group velocity at a single frequency.

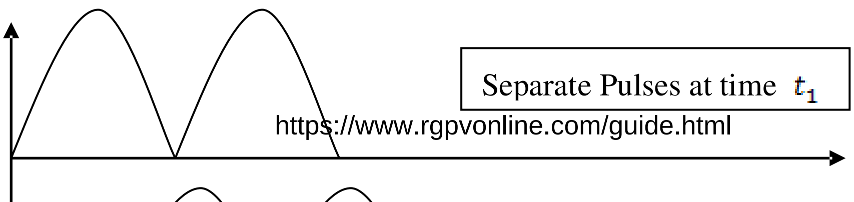

Fig. 3.5 Broadening and attenuation of two adjacent pulses as they travel along the fiber

Material Dispersion: Arises due to the variations of the refractive index of the core material as a function of wavelength.

Waveguide Dispersion: Causes pulse spreading only part of the optical power propagating along the fiber is confined in the core . Dispersion arises because of the fraction of light power propagating in the cladding travels faster than the light confined in the core, since the index is lower in the cladding.

Polarization Mode dispersion: results from the fact that light signal energy at a given wavelength in a single mode fiber actually occupies two orthogonal polarization state or modes. At the start of the fiber the two polarization states are aligned. However since fiber material is not perfectly uniform throughout its length, each polarization mode will encounter slightly different refractive index.

3.7 Characteristics of Single Mode Fibers

These characteristics include index profile configurations used to produce different types of fibers, the concept of cut off wavelength, signal dispersion designations and calculations.

Refractive Index Profile: It is possible to modify the waveguide dispersion by changing from a simple step-index design to more complex index profiles for the cladding, thereby creating different chromatic-dispersion characteristics in single mode fibers. The four refractive index profiles for fiber design are 1310nm optimized fibers, dispersion shifted fibers, dispersion flattened fibers and large effective core three dimensional profiles for several different types of single mode fibers.

1310nm optimized single mode fibers are either the matched cladding or depressed cladding. Matched cladding fibers have uniform refractive index throughout the cladding. In depressed cladding fibers the cladding material next to the core has lower index than outer cladding region. By creating fiber with large negative waveguide dispersion and assuming the same values for material dispersion can then shift the zero dispersion point to longer wavelengths. The resulting optical fiber is known as Dispersion shifted fiber.To reduce the effects of fiber nonlinearities, fiber designers developed the non zero dispersion shifted fibers (NZDSF). The large core areas in these fibers reduce the effects of fiber nonlinearities.

An alternative fiber design concept is to distribute the dispersion minimum over a wider spectral range. This approach is known as dispersion flattening.

3.8 Cutoff Wavelength

The cutoff wavelength of first higher mode is an important transmission parameter for single mode fibers, since it separates the single mode from multimode regions . Single mode operation occurs above the theoretical cut off wavelength given by.

$$\lambda_{c;th}=\frac{2\pi a}{V}\left(n_1^2-n_2^2\right)^{1/2}$$

With V=2.405 for step index fibers.

3.9 Dispersion Calculation

The total chromatic dispersion in single mode fibers consists mainly of material and waveguide dispersions. The resultant intramodal or chromatic dispersion is given by

$$D(\lambda)=\frac{d\tau}{Ld\lambda}$$

Where τ is a group delay. The dispersion is commonly expressed in ps/(nm.km). The broadening σ of an optical pulse over a fiber of length L is given by

$\sigma = D(\lambda)L\,\sigma$

Where σ is the half power spectral width of the optical source. To measure the dispersion, one examines the pulse delay over a desired wavelength range.

3.10 Bending Loss

Macro bending and micro bending losses are important in the design of single mode fibers. These fibers are principally evident in 1550nm region, and show up a rapid increase in attenuation when fiber is bent smaller than a certain bend radius. The lower the cutoff wavelength relative to the operating wavelength, the more susceptible single mode fibers are for bending. The bending losses are primarily a function of the mode field diameter , the smaller the bending loss. This is true for both match-clad and depressed clad fibers.