G PULLAIAH COLLEGE OF ENGINEERING AND TECHNOLOGY: KURNOOL

DEPT OF ECE

OFC LECTURE NOTES

UNIT-4

BASIC TERMS AND DEFINITIONS:

Avalanche photodiode	A photodiode that takes advantage of avalanche multiplication of photocurrent to convert one photon to multiple electrons.
Detector	A device such a photodiode or photodetector that converts optical energy into electrical energy. They can be made from silicon, germanium, gallium arsenide, indium gallium arsenide or from other semiconductors, depending on the wavelengths to detect. The positive-intrinsic-negative (PIN) and the avalanche photodiode (APD) types are used in fiber optics. PIN types can be used for analog or digital systems, while APDs with their internal amplification can only be used in digital systems.
Detector-amplifier	A device in which an optical detector is packaged with electronic amplification circuitry.
PIN diode	Positive intrinsic negative diode, a type of photodiode used to convert optical signals in a receiver. Can be used with both analog and digital systems.
Photodetector	An electro-optic device that transforms light energy into electrical energy.
Photodiode	A semiconductor that converts light into an electrical signal, used in fiber optic receivers.
splices	The splices are generally permanent fiber joints, whereas connectors are temporary fiber joints. Splicing is a sort of soldering.
Responsivity	Responsivity is defined as the ratio of output photo current to the incident optical power.
Threshold Current	The threshold current is conventionally defined by extrapolation of the lasing region of the Power Vs Current curve. At high power outputs, the slope of the curve decreases because of junction heating.
Photocurrent	The high electric field present in the depletion region causes the carriers to separate and be collected across the reverse- biased junction. This gives to a current flow in the external circuit, with one electron flowing for every carrier pair generated. This current flow is known as photocurrent.
Impact Ionization	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 energy so that it ionizes bound electrons in the valence band upon colliding with them. This current multiplication mechanism is

	known as impact ionization.
Quantum Limit	To find the minimum received optical power required for a specific bit error rate performance in a digital system. This minimum received power level is known as the Quantum Limit.
Thermal noise	Thermal noise is due to the random motion of electrons in a conductor.Thermal noise arising from the detector load resistor and from the amplifier electronics tend to dominate in applications with low signal to noise ratio.

Concepts

Avalanche Photodiode (APD)

When a p-n junction diode is applied with high reverse bias breakdown can occur by two separate mechanisms direct ionization of the lattice atoms, zener breakdown and high velocity carriers impact ionization of the lattice atoms called avalanche breakdown. APDs uses the avalanche breakdown phenomena for its operation. The APD has its internal gain which increases its responsivity.

Fig. 3.2.5 shows the schematic structure of an APD. By virtue of the doping concentration and physical construction of the n^+ p junction, the electric filed is high enough to cause impact ionization. Under normal operating bias, the I-layer (the p^- region) is completely depleted. This is known as **reach through** condition, hence APDs are also known as **reach through APD** or **RAPDs**.]

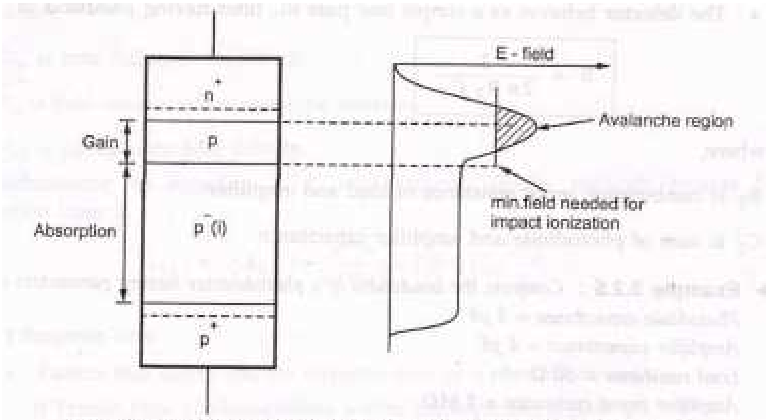

Fig. 3.2.5 APD schematic and variation of E-field across diode

Similar to PIN photodiode, light absorption in APDs is most efficient in I-layer. In this region, the E-field separates the carriers and the electrons drift into the avalanche region where carrier multiplication occurs. If the APD is biased close to breakdown, it will result in reverse leakage current. Thus APDs are usually biased just below breakdown, with the bias voltage being tightly controlled.

The multiplication for all carriers generated in the photodiode is given as –

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

I_M = Average value of total multiplied output current.

I_P = Primary unmultiplied photocurrent

Responsivity of APD is given by –

$$\boxed{\Re_{APD} = \frac{\eta q}{h\nu} M} \qquad \because \nu = \frac{c}{\lambda}$$

$$\Re_{APD} = \Re_o M$$

$\Re_0$ = Unity gain responsivity.

PIN Photodiode

PIN diode consists of an intrinsic semiconductor sandwiched between two heavily doped.

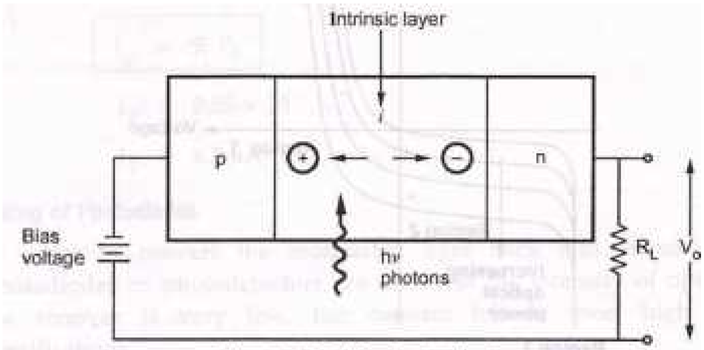

Fig. 3.2.2 PIN photodiode

Sufficient reverse voltage is applied so as to keep intrinsic region free from carries, so its resistance is high, most of diode voltage appears across it, and the electrical forces are strong within it. The incident photons give up their energy and excite an electron from valance to conduction band. Thus a free electron hole pair is generated, these are called as **photocarriers**. These carriers are collected across the reverse biased junction resulting in rise in current in external circuit called **photocurrent**.

In the absence of light, PIN photodiodes behave electrically just like an ordinary rectifier diode. If forward biased, they conduct large amount of current.

PIN detectors can be operated in two modes : **Photovoltaic** and **photoconductive**. In photovoltaic mode, no bias is applied to the detector. In this case the detector works very slow, and output is approximately logarithmic to the input light level. Real world fiber optic receivers never use the photovoltaic mode.

In photoconductive mode, the detector is reverse biased. The output in this case is a current that is very linear with the input light power.

The intrinsic region some what improves the sensitivity of the device. It does not provide internal gain. The combination of different semiconductors operating at different wavelengths allows the selection of material capable of responding to the desired operating wavelength.

Optical Receiver Design

An optical receiver system converts optical energy into electrical signal, amplify the signal and process it. Therefore the important blocks of optical receiver are :

- Photodetector / Front-end
- Amplifier / Liner channel
- Signal processing circuitry / Data recovery.

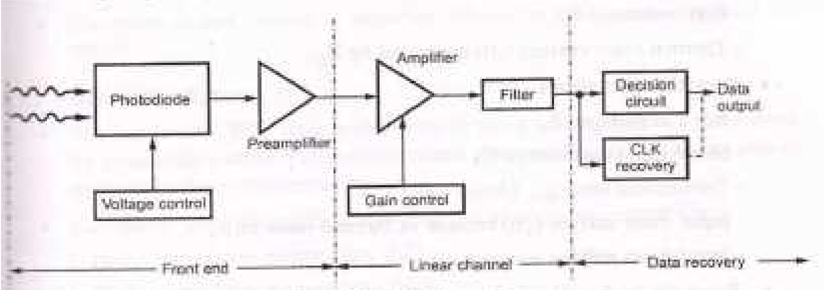

Fig. 5.1.1 Optical receiver

Noise generated in receiver must be controlled precisely as it decides the lowest signal level that can be detected and processed. Hence noise consideration is an important factor in receiver design. Another important performance criteria of optical receiver is average error probability.

Splicing

A permanent joint formed between two individual optical fibers in the field is known as splicing. The fiber splicing is used to establish optical fiber links, where smaller fiber lengths are needed to be joined and where there is no requirement for repeated connection and disconnection.

Splicing can be divided into two broad categories depending on the splicing technique utilized. These are fusion-splicing, mechanical or welding splicing.

Fusion Splicing

Fusion splicing of single fibers involves the heating of the two prepared fiber ends to their fusing point with sufficient axial pressure between the two optical fibers. It is essential that the stripped fiber ends are adequately positioned and clamped with the aid of inspection microscope.

The most widely used heating technique is an electric arc. This technique offers advantage of consistent, easily controlled heat with adaptability for use under field conditions.

The welding of 2 fibers can be shown as illustrated in the following figure.

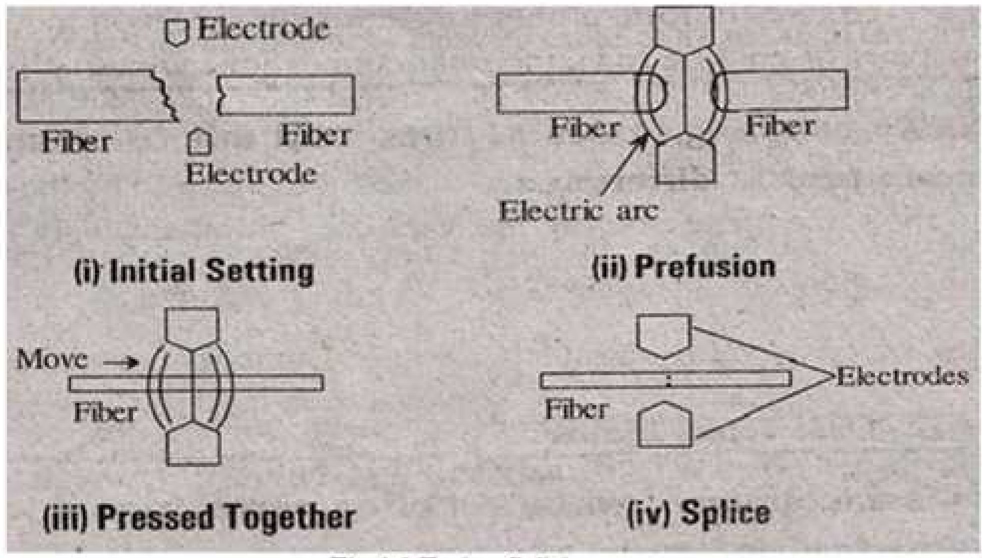

Fig 4.1 Fusion Splicing

The figure shows basic arc fusion process, which involves the rounding of the fiber ends with a low energy discharge before pressing the fibers together and fusing with a stronger arc.

This technique is called perfusion. It removes the requirement for fiber end preparation. It has been utilized with multimode fibers giving average splice losses of 0.09 dB.

Fusion splicing of single mode fibers with arc diameters between 5 and 10 um present problems of more critical fiber alignment (lateral offsets of less than 1 um are required for low loss joints).

Splice uncertain losses below 0.3 dB may be achieved due to self alignment phenomenon which partially compensates for any lateral offset.

The drawback with fusion splicing is that the heat necessary to fuse the fibers may weaken the fiber in the vicinity of the splice.

The tensile strength' of the fused fiber may be as low as 30% as that of the uncoated fiber before fusion. The fiber fracture occurs in the heat affected zone adjacent to the fused joint. The reduced tensile strength is attributed, to the combined effects of surface damage caused by handling, surface defect growth during heating and induced stresses due to changes in chemical composition. Hence it is necessary that splice is packaged so as to reduce tensile loading upon the fiber in the vicinity of the splice.

Adhesive Splicing:

A common method involves the use of ah accurately produced rigid alignment tube into which the prepared fiber ends are permanently, bonded. This snug tube splice may utilize a glass or ceramic capillary with an inner diameter just large enough to accept the optical fibers. Transparent adhesive (e.g. epoxy resin) is injected through a transverse bore in die capillary to give mechanical sealing and index matching of the splice. However, in general, snug tube splices exhibit problems with capillary tolerance requirements.

A mechanical splicing-technique which avoids the critical tolerance requirements of the snug tube splice is shown in figure 4.3.This loose tube splice uses an over sized square section metal tube which easily accepts the prepared fiber ends. Transparent adhesive is first insulated in the tube followed by the fibers. The splice is self aligning when the fibers are curved in the same plane, forcing the fiber ends simultaneously into the same corner of tube.

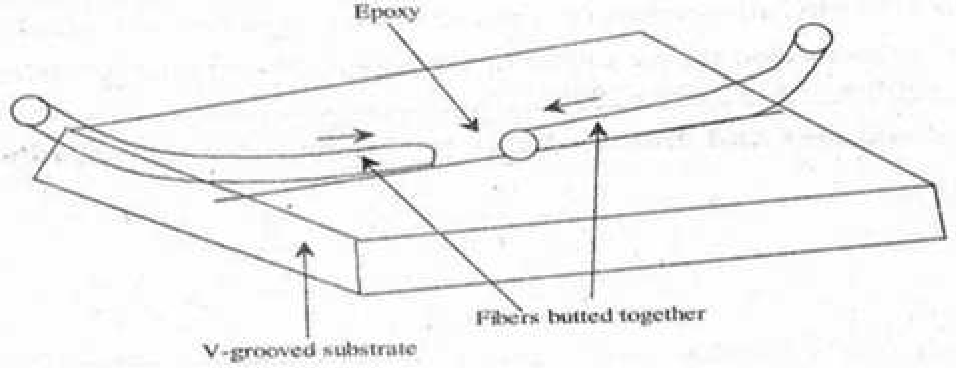

Fig 4.3 V-Groove Splices

Other common splicing techniques involve the use of grooves to secure the fibers to be jointed. A simple method utilized a V-groove into which the two prepared fiber ends are pressed. The V-groove splice which is shown in figure gives alignment of the prepared fiber ends through insertion in the groove. The splice is made permanent by securing the fibers in the V-groove with epoxy resin (i.e., transparent adhesive).

Photo detector

Photo detector is an essential component of an optical fiber communication system. Its function is to convert the received optical signal into an electrical signal which is amplified before further processing. The requirements for photo detector can be given as follows.

(i) They should have high sensitivity at operating wavelength.

(ii) It should have high fidelity to reproduce the original waveform effectively.

(iii) It should produce maximum electrical signal for a given amount of optical power.

(iv) It should have short response time to obtain a suitable bandwidth.

(v) Dark currents, leakage currents, shunt conductance should be low.

(vi) Performance characteristics should be independent of changes in ambient conditions.

(vii) The physical size of detector must be small for effective coupling.

(viii) Detector should not require excessive bias voltages or currents.

(ix) It must be highly reliable and must be capable of continuous stable operation at room temperature.

(x) It should be economical.

The detector must satisfy the above requirements of performance and compatibility.

Photodiode

Photodiodes are preferred for photo detection in optical system. The photodiodes provide good performance and compatibility with relatively low cost. These photodiodes are made from semiconductors such as silicon, germanium and an increasing number of III-V alloys. Internal photoemission process may take place in both intrinsic and extrinsic semiconductors. The intrinsic absorption process is preferred as they have fast response coupled with efficient absorption of photons.

These photodiodes are sensitive, have adequate speed, negligible shunt, conductance, low dark current, long term stability. Thus they are widely used. Avalanche photodiodes are also widely employed in fiber communication system. They have very sophisticated structure.

Specifications of a Semiconductor Photo Diode

The important performance parameters of a semiconductor photodiode are described below.

1. Responsivity

The ratio of generated photocurrent to incident light power typically expressed in A/W when used in photo conductive mode. The responsivity may also be expressed as quantum efficiency or the ratio of the number of photo generated carriers to incident photons and thus, a unit less quantity. The typical values for responsivity are, 0.65 for A/W silicon at 900 nm, 0.45 A/W for germanium at 1.3 μm and 0.9 A/W for InGaAs at 1.3 μm.

2. Dark Current

The current through the photodiode in the absence of light, when it is operated in photoconductive m dark current includes photocurrent generated by background radiation and the saturation current of the semiconductor junction. Dark current must be accounted for calibration if a photodiode is used to make an accurate optical measurement. It is also a source of noise when a photo diode is used in an optical communication system.

3. Noise Equivalent Power (NEP)

The minimum input optical power to generate photocurrent, equal to the r.m.s noise current in a 1 Hz bandwidth. The related characteristic directivity *DIS* the inverse of NEP i.e., 1/NEP and the specific directivity D^* is the directivity normalized to the area, A of the photodiode i.e.,

$$D^{*}=D\sqrt{A}$$

4. Quantum Efficiency

The photodiode's capability to convert light energy to electrical energy is referred as quantum efficiency, it can be also described as the ratio of number of electron-hole pairs generated to the number of incident photons. In a practical photodiode, the quantum efficiency of the detector ranges from 30 to 95%.

5. Sensitivity

It is a measure of the effectiveness of a detector in producing an electrical signal at the peak sensitivity wavelength.

6. Rise time

The time required for a detector output to reach from 10 to 90% of its final value.

Fiber Optic Receiver

The terra receiver at the output end of the fiber optic cable refers to both a light detecting transducer and its related electronics, which provides any necessary signal conditioning to restore the signal to its original shape at the input, as well as additional signal amplification. To interface the receiver with the optical fiber, the proper match between light source, fiber optic cable and light detector is required. In the AM transmission system, the optical power input at the fiber is modulated so that the photo detector operating in the photocurrent mode must provide good linearity, speed and stability.

The photodiode produces no electrical gain and is therefore followed by circuits that amplify electrical voltage and power to drive the coaxial cable. Figure below illustrates the block diagram for the optical fiber receiver unit.

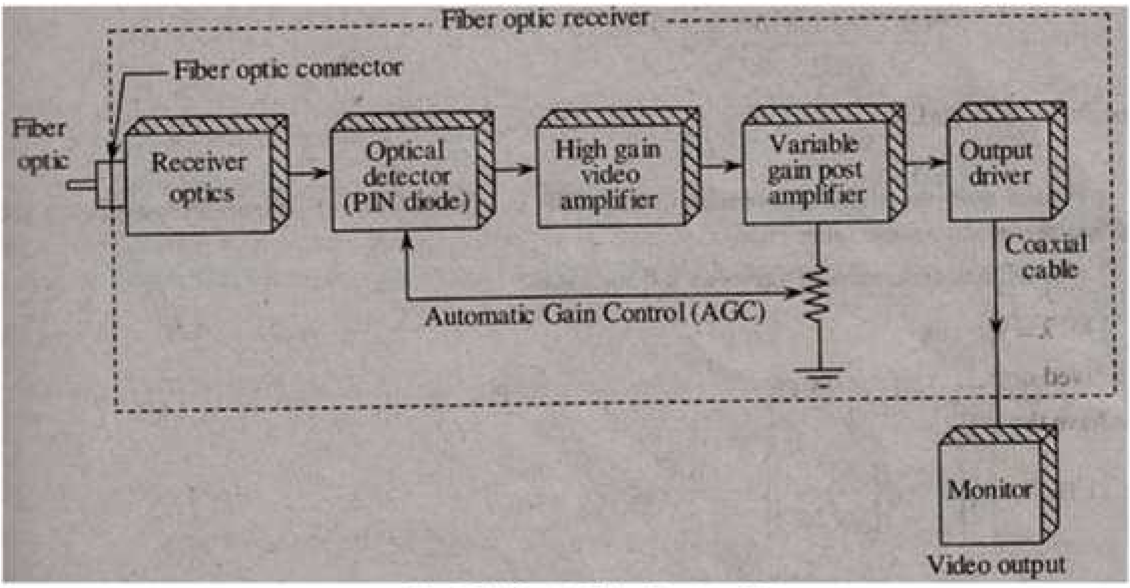

Fig 6.8.1 Optical Fiber Receiver Unit

As light enters from the receiver end of an optical fiber, it spreads out with a divergence approximately equal to the acceptance cone angle at the transmitter end of the fiber. Photodiodes are packaged with lenses on their housings so that the lens collects this output energy and focuses it down onto the photodiode-sensitive area. The most common fiber optic receiver uses a photodiode to convert the incident light from the fiber into electrical energy. After the light energy is converted into an electrical signal by the photodiode, it is linearly amplified and conditioned to be suitable for transmission over standard coaxial cable to a monitor or recorder.

Quantum Limit

The minimum received optical power required for a particular bit error rate performance using an ideal photo detector (which has zero dark current and unity quantum efficiency) is referred as quantum efficiency. In this case, the performance of the system will depend only on the photo detection statistics as the remaining all the system parameters are considered to be ideal. Due to several nonlinear distortions and noise effects in the transmission link, the practical values of most of the receiver sensitivities will be around 20 dB higher than the quantum limit. It is also very important to differentiate average power and peak power while specifying he quantum limit.

Dark Current

In the absence of light, the current that flows continuously through the basic circuit of the device is referred as dark current or the leakage current that flows when the photodiode is in the dark and a reverse voltage is applied across the junction is referred as dark current. This voltage may be low as 10 mV or as high as 50 V and the dark current may vary from pA to uA depending on the junction area and the process used.

The dark current is temperature dependent. The rule of thumb is that the dark current will approximately double for every 10°C increase in ambient temperature. However, specific diode types can vary considerably from this relationship.

b)Sensitivity

The sensitivity of the receiver is defined as the minimum amount of optical power required to achieve a specific receiver performance. The receiver takes many signals such as synchronous signals (to recover the clock signal similar to that is used at transmitter), decoded data and errors. So, in order to generate a correct signal in the presence of all these signals, a receiver should have high sensitivity. If it has high sensitivity it will be even able to detect low level optical signals. Thus, the higher the sensitivity, the more efficiently the receivers can detect the attenuated on low level signals. The sensitivity of receiver can be sketched taking the data rate and optical power that the receiver can detect.

Bit Error Rate (BER)

In practice, that there are several standard ways of measuring the rate of error occurrences in a digital data stream. One common approach is to divide the number N_e of errors occurring over a certain time interval t by number N_t of pulses (ones and zeros) transmitted during this interval.

This is called either the error rate of the bit error rate, which is commonly abbreviated as BER. Thus, we have

$$BER = N_e/N_t$$