SIDDARTHA INSTITUTE OF SCIENCE AND TECHNOLOGY: PUTTUR
(AUTONOMOUS)

Department of Electronics and Communication Engineering

FIBER OPTIC COMMUNICATIONS (20EC0433)

UNIT –I

Introduction to Optical Fibers

Introduction

Fiber-optic communication is a method of transmitting information from one place to another by sending pulses of light through an optical fiber. The light forms an electromagnetic carrier wave that is modulated to carry information. Fiber is preferred over electrical cabling when high bandwidth, long distance, or immunity to electromagnetic interference are required. This type of communication can transmit voice, video, and telemetry through local area networks, computer networks, or across long distances.

Optical fiber is used by many telecommunications companies to transmit telephone signals, Internet communication, and cable television signals. Researchers at Bell Labs have reached internet speeds ofover 100 peta bit ×kilometer per second using fiber-optic communication.

The process of communicating using fiber-optics involves the following basic steps:

1. creating the optical signal involving the use of a transmitter, usually from an electrical signal
2. relaying the signal along the fiber, ensuring that the signal does not become too distorted or weak
3. receiving the optical signal
4. converting it into an electrical signal

Historical Development

- Fiber optics deals with study of propagation of light through transparent dielectric wave guides. The fiber optics are used for transmission of data from point to point location. Fiber optic systems currently used most extensively as the transmission line between terrestrial hardwired systems.

- The carrier frequencies used in conventional systems had the limitations in handling the volume and rate of the data transmission. The greater the carrier frequency larger the available band width and information carrying capacity.

First generation

The first generation of light wave systems uses GaAs semiconductor laser and operating region was near 0.8 μm. Other specifications of this generation are as under:

i) Bit rate : 45 Mb/s

ii) Repeater spacing :10 km

Second generation

i) Bit rate : 100Mb/s to 1.7 Gb/s

ii) Repeater spacing :50 km
iii) Operating wave length:1.3μm

Third generation

i) Bit rate : 10 Gb/s
ii) Repeater spacing :100 km
iii) Operating wave length:1.55μm

Fourth generation

i) Bit rate : 10 Tb/s
ii) Repeater spacing :>10000 km
iii) Operating wave length:1.45 to 1.62μm

Fifth generation

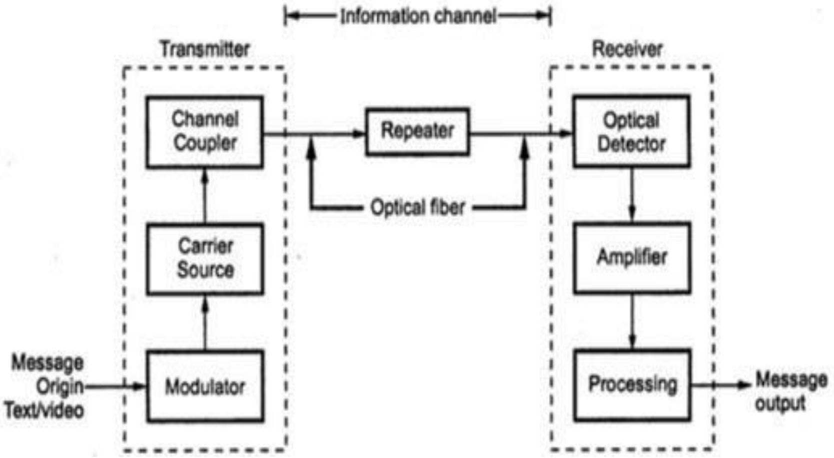
i) Bit rate : 40-160 Gb/s
ii) Repeater spacing : 24000 km - 35000 km
iii) Operating wave length:1.53 to 1.62 μm

General Optical Fiber Communication System

Basic block diagram of optical fiber communication system consists of following important blocks.

1. Transmitter
2. Information channel
3. Receiver

Fig 1.1: Block Diagram of Optical Fiber Communication System



Message origin :

Generally message origin is from a transducer that converts a non-electrical message into an electrical signal. Common examples include microphones for converting sound waves into currents and video (TV) cameras for converting images into current. For data transfer between computers, the message is already in electrical form.

Modulator:

The modulator has two main functions.

1) It converts the electrical message into the proper format.
2) It impresses this signal onto the wave generated by the carrier source.

Two distinct categories of modulation are used i.e. analog modulation and digital modulation.

Carrier source:

Carrier source generates the wave on which the information is transmitted. This wave is called the carrier. For fiber optic system, a laser diode (LD) or a light emitting diode (LED) is used. They can be called as optic oscillators. They provide stable, single frequency waves with sufficient power for long distance propagation.

Channel coupler:

Coupler feeds the power into the information channel. For an atmospheric optic system, the channel coupler is a lens used for collimating the light emitted by the source and directing this light towards the receiver. The coupler must efficiently transfer the modulated light beam from the source to the optic fiber. The channel coupler design is an important part of fiber system because of possibility of high losses.

Information channel:

The information channel is the path between the transmitter and receiver. In fiber optic communications, a glass or plastic fiber is the channel. Desirable characteristics of the information channel include low attenuation and large light acceptance cone angle. Optical amplifiers boost the power levels of weak signals. Amplifiers are needed in very long links to provide sufficient power to the receiver. Repeaters can be used only for digital systems. They convert weak and distorted optical signals to electrical ones and then regenerate the original digital pulse trains for further transmission.

Another important property of the information channel is the propagation time of the waes travelling along it. A signal propagating along a fiber normally contains a range of optic frequencies and divides its power along several ray paths. This results in a distortion of the propagating signal. In a digital system, this distortion appears as a spreading and deforming of the pulses. The spreading is so great that adjacent pulses begin to overlap and become unrecognizable as separate bits of information.

Advantages of Optical Fiber Communications :

Optical fibers have largely replaced copper wire communications in core networks in the developed world, because of its advantages over electrical transmission. Here are the main advantages of fiber optic transmission.

1. Wide bandwidth

The light wave occupies the frequency range between 2×10^{12} Hz to 3.7×10^{12} Hz. Thus the information carrying capability of fiber optic cables is much higher.

2. Low losses

Fiber optic cables offers bery less signal attenuation over long distances. Typically it is less than 1 dB/km. This enables longer distance between repeaters.

3. Immune to cross talk

Fiber optic cables has very high immunity to electrical and magnetic field. Since fiber optic cables are non-conductors of electricity hence they do not produce magnetic field. Thus fiber optic cables are immune to cross talk between cables caused by magnetic induction.

4. Interference immune

Fiber optic cables are immune to conductive and radiative interferences caused by electrical noise sources such as lighting, electric motors, fluorescent lights.

5. Light weight

As fiber cables are made of silica glass or plastic which is much lighter than copper or aluminium cables. Light weight fiber cables are cheaper to transport.

6. Small size

The diameter of fiber is much smaller compared to other cables, therefore fiber cable is small in size, requires less storage space.

7. More strength

Fiber cables are stronger and rugged hence can support more weight.

8. Security

Fiber cables are more secure than other cables. It is almost impossible to tap into a fiber cable as they do not radiate signals. No ground loops exist between optical fibers hence they are more secure.

9. Long distance transmission

Because of less attenuation transmission at a longer distance is possible.

10. Environment immune

Fiber cables are more immune to environmental extremes. They can operate over large temperature variations. Also they are not affected by corrosive liquids and gases.

11. Sage and easy installation

Fiber cables are safer and easier to install and maintain. They are non-conductors hence there is no shock hazards as no current or voltage is associated with them. Their small size and light weight feature makes installation easier.

12. **Less cost**

Cost of fiber optic system is less compated to any other system.

Disadvantages of Optical Fiber Communicaitons

1. High initial cost

The intial cost of installation or setting up cost is very high compared to all other system.

2. Maintenance and repairing cost

The maintenance and repairing of fiber optic systems is not only difficult but expensive also.

3. **Jointing and test procedures**

Since optical fibers are of very small size. The fiber joining process is very constly and requires skilled manpower.

4. Tensile stress

Optical fibers are more susceptible to buckling, bending and tensile stress than copper cables. This leads to restricted practice to use optical fiber technology to premises and floor backbones with a few interfaces to the copper cables.

5. **Short links**

Even though optical fiber cables are inexpensive, it is still not cost effective to replace every small conventional connector (e.g. between computers and peripherals), as the price of optoelectronic transducers are very high.

6. Fiber losses

The amount of optical fiber available to the photo detector at the end of fiber length depends on various fiber losses such as scattering, dispersion, attenuation and reflection.

Applications of Optical Fiber Communicaitons

Applications of optical fiber communications include telecommunications, data communications, video control and protection switching, sensors and power applications.

1**. Telephone networks**

Optical waveguide has low attenuation, high transmission bandwidth compated to copper lines, therefore numbers of long haul co-axial trunks l;links between telephone exchanges are being replaced by optical fiber links.

2. Urban broadband service networks

Optical waveguide provides much larger bandwidth than co-axial cable, also the number of repeaters required is reduced considerably.

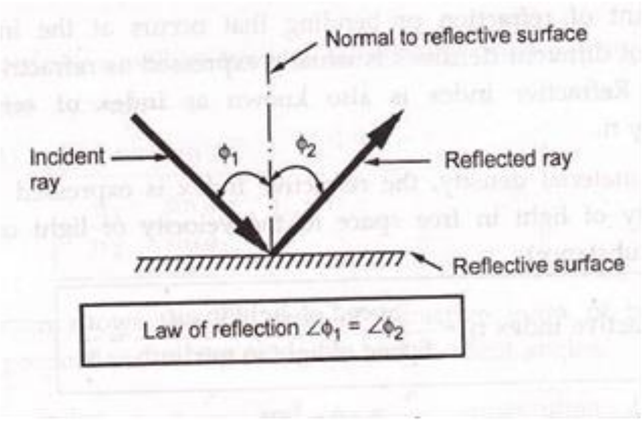
Modern suburban communications involves videotext, videoconferencing video telephony, switched broadband communication network.

Ray Transmission Theory

Before studying how the light actually propagates through the fiber, laws governing the nature of light must be studied. These are called as laws of optics (Ray theory). There is conception that light always travels at the same speed. This fact is simply not true. The speed of light depends upon the material or medium through which it is moving. In free space light travels at its maximum possible speed i.e. 3×10^8 m/s. When light travels through a material it exhibits certain behaviour explained by laws of reflection, refraction.

Reflection

The law of reflection states that, when a light ray is incident upon a reflective surface at some incident angle Φ_1 from imaginary perpendicular normal, the ray will be reflected from the surface at some angle Φ_2 from normal which is equal to the angle of incidence.



Refraction

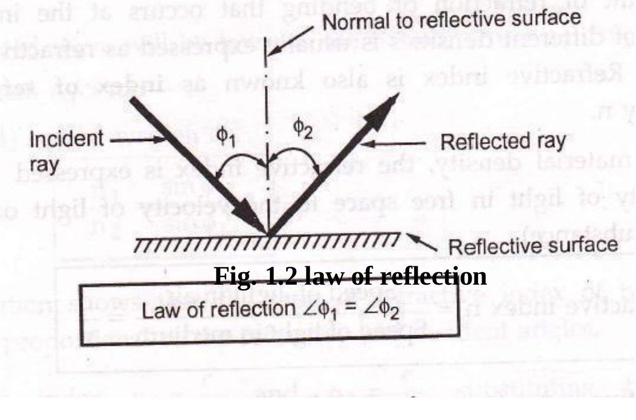


Fig. 1.2 law of reflection

Refraction occurs when light ray passes from one medium to another i.e. the light ray changes its direction at interface. Refraction occurs whenever density of medium changes. E.g. refraction occurs at air and water interface, the straw in a glass of water will appear as it is bent.

The refraction can also observed at air and glass interface.

- When wave passes through less dense medium to denser medium, the wave is refracted (bent) towards the normal. Fig.3 shows the refraction phenomena.
- The refraction (bending) takes place because light travels at different speed in different mediums. The speed of light in free space is higher than in water or glass.

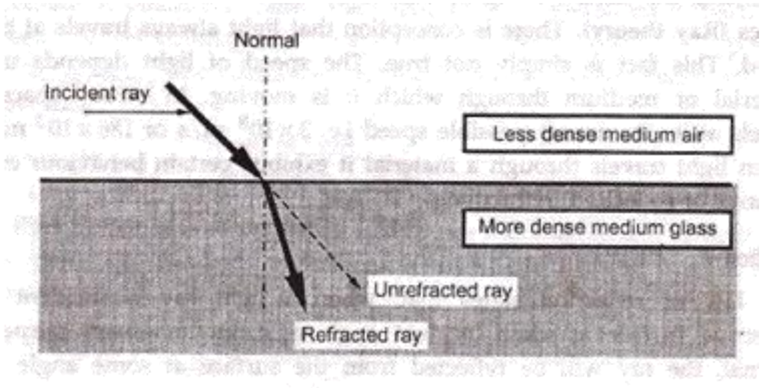


Fig. 1.3 Refraction

Refractive Index

The amount of refraction or bending that occurs at the interface of two materials of different densities is usually expressed as refractive index of two materials. Refractive index is also known as index of refraction and is denoted by n. Based on material density, the refractive index is expressed as the ratio of the velocity of light in free space to the velocity of light of the dielectric material (substance).

$$\boxed{\text{Refractive index } n = \frac{\text{Speed of light in air}}{\text{Speed of light in medium}} = \frac{c}{v}}$$

The refractive index for vacuum and air or 1.0 for water it is 1.3 and for glass refractive index is 1.5.

Snell's Law

- Snell's law states how light ray reacts when it meets the interface of two media having different indexes of refraction.

- Let the two medias have refractive indexes n1 and n2 where n1 >n2.

Φ_1 and Φ_2 be the angles of incidence and angle of refraction respectively. Then according to Snell's law, a relationship exists between the refractive index of both materials given by

- A refractive index model for Snell's law is shown in Fig.1. 4.

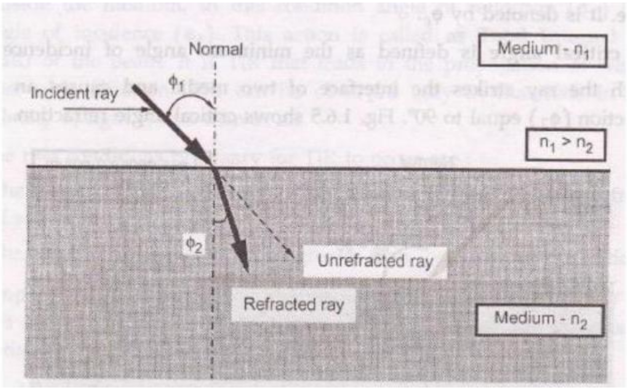


Fig. 1.4 Refractive model for Snells Law

Critical Angle

When the angle of incidence ($\Phi1$) is progressively increased, there will be progressive increase of refractive angle ($\Phi2$). At some condition $\Phi1$) the refractive angle ($\Phi2$) becomes 90o to the normal. When this happens the refracted light ray travels along the interface. The angle of incidence ($\Phi1$) at the point at which the refractive angle ($\Phi1$) becomes 90o is called the critical angle. It is denoted by Φc.

The critical angle is defined as the minimum angle of incidence (Φ_1) at which the ray strikes the interface of two media and causes an agnle of refraction (Φ_2) equal to 90^o. Fig.1.5 shows critical angle refraction.

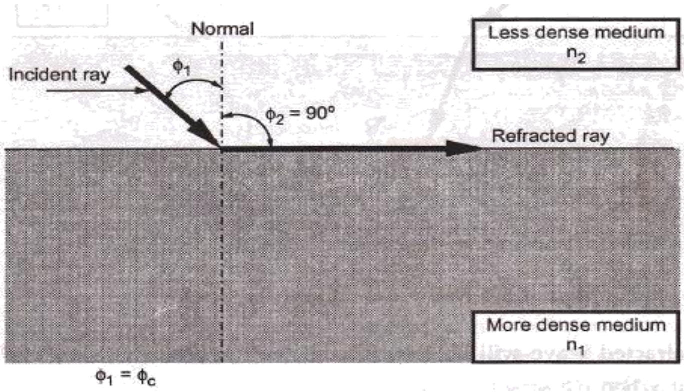


Fig.1.5 Critical Angle

Total Internal Reflection (TIR)

When the incident angle is increased beyond the critical angle, the light ray does not pass through the interface into the other medium. This gives the effect of mirror exist at the interface with no possibility of light escaping outside the medium. In this condition angle of reflection is equal to angle of incidence. This action is called as TIR of the beam.

Numerical Aperture (NA)

The numerical aperture (NA) of a fiber is a figure of merit which represents its light gathering capability. Larger the numerical aperture, the greater the amount of light accepted by fiber. The acceptance angle also determines how much light is able to be enter the fiber and hence there is relation between the numerical aperture and the cone of acceptance.

$$\text{Numerical aperture (NA)} = \sin \phi_{0(\max)}$$

$$NA = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

For air $n_0 = 1$

$$\therefore \quad NA = \sqrt{n_1^2 - n_2^2}$$

Optical fiber structure

An optical fiber consists of three concentric elements, the core, the cladding and the outer coating, often called the buffer. The core is usually made of glass or plastic. The core is the light-carrying portion of the fiber. The cladding surrounds the core. The cladding is made of a material with a slightly lower index of refraction than the core. This difference in the indices causes total internal reflection to occur at the core-cladding boundary along the length of the fiber. Light is transmitted down the fiber and does not escape through the sides of the fiber.

- Fiber Optic Core:

  The inner light-carrying member with a high index of refraction.

- Cladding:

  The middle layer, which serves to confine the light to the core. It has a lower index of refraction.

- Buffer:

  The outer layer, which serves as a "shock absorber" to protect the core and cladding from damage. The coating usually comprises one or more coats of a plastic material to protect the fiber from the physical environment. Sometimes metallic sheaths are added to the coating for further physical protection.

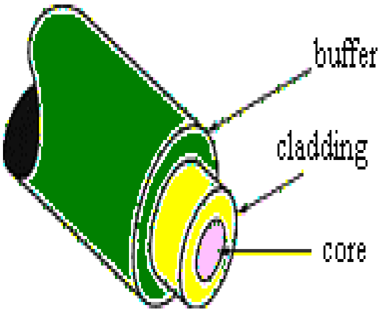


Fig.1.6 optical fiber structure

Types of Rays

There exist three different types of rays.

The **skew rays** does not pass through the center, as show in Fig. 1.7 (a). The skew rays reflects off from the core cladding boundaries and again bounces around the outside of the core. It takes somewhat similar shape of spiral of helical path.

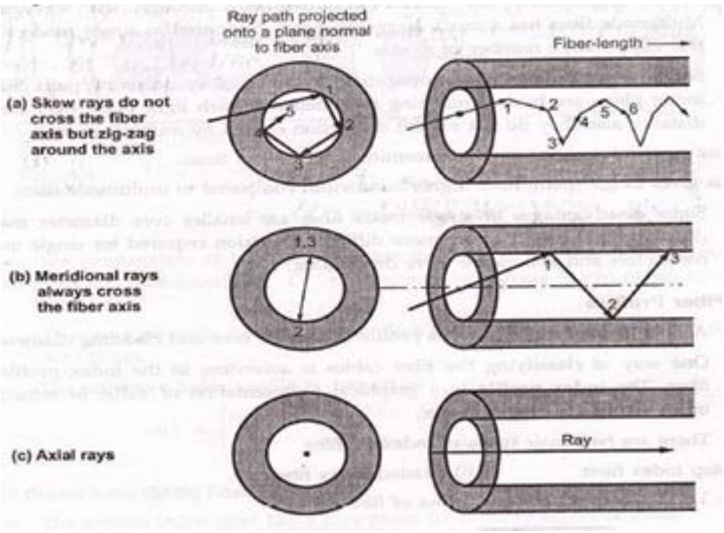


Fig.1.7. Different rays

The **meridional ray** enters the core and passes through its axis. When the core surface is parallel, it will always be reflected to pass through the enter. The meridional ray is shown in fig. 6 (b).

The **axial ray** travels along the axis of the fiber and stays at the axis all the time. It is shown in fig. 1.6.11 (c).

Modes of Fiber

Fiber cables can also be classified as per their mode. Light rays propagate as an electromagnetic wave along the fiber. The two components, the electric field and the magnetic field form patterns across the fiber. These patterns are called modes of transmission. The mode of a fiber refers to the number of paths for the light rays within the cable. According to modes optic fibers can be classified into two types.

i) Multimode fiber ii) single mode fiber

Multimode fiber

Multimode fiber was the first fiber type to be manufactured and commercialized. The term multimode simply refers to the fact that numerous modes (light rays) are carried simultaneously through the waveguide. Multimode fiber has a much larger diameter, compared to single mode fiber, this allows large number of modes.

Single mode fiber

Single mode fiber allows propagation to light ray by only one path. Single mode fibers are best at retaining the fidelity of each light pulse over longer distance also they do not exhibit dispersion caused by multiple modes. Thus more information can be transmitted per unit of time. This gives single mode fiber higher bandwidth compared to multimode fiber.

Some disadvantages of single mode fiber are smaller core diameter makes coupling light into the core more difficult. Precision required for single mode connectors and splices are more demanding.

Optic Fiber Configurations

Depending on the refractive index profile of fiber and modes of fiber there exist three types of optical fiber configurations. These optic-fiber configurations are

i) Single mode step index fiber.
ii) Multimode step index fiber.
iii) Multimode graded index fiber.

Single mode Step index Fiber

- In single mode step index fiber has a central core that is sufficiently small so that there is essentially only one path for light ray through the cable. The light ray is propagated in the fiber through reflection. Typical core sizes are 2 to 15 µm. Single mode fiber is also known as fundamental or monomode fiber.

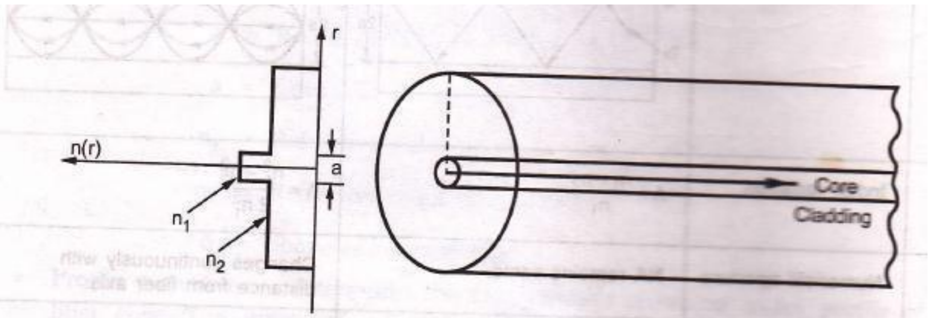


Fig.1.7 single mode step index fiber

- Single mode fiber will permit only one mode to propagate and does not suffer from mode delay differences. These are primarily developed for the 1300 nm window but they can be also be used effectively with time division multiplex (TDM) and wavelength division multiplex (WDM) systems operating in 1550 nm wavelength region.

- The core fiber of a single mode fiber is very narrow compared to the wavelength of light being used. Therefore, only a single path exists through the cable core through which light can travel. Usually, 20 percent of the light in a single mode cable actually travels down the cladding and the effective diameter of the cable is a blend of single mode core and degree to which the cladding carries light. This is referred to as the 'mode field diameter', which is larger than physical diameter of the core depending on the refractive indices of the core and cladding.

- The disadvantage of this type of cable is that because of extremely small size interconnection of cables and interfacing with source is difficult. Another disadvantage of single mode fibers is that as the refractive index of glass decreases with optical wavelength, the light velocity will also be wavelength dependent. Thus the light from an optical transmitter will have definite spectral width.

Multimode step Index Fiber

- Multimode step index fiber is more widely used type. It is easy to manufacture. Its core diameter is 50 to 1000 μm i.e. large aperture and allows more light to enter the cable. The light rays are propagated down the core in zig-zag manner. There are many many paths that a light ray may follow during the propagation.

- The light ray is propagated using the principle of total internal reflection (TIR). Since the core index of refraction is higher than the cladding index of refraction, the light enters at less than critical angle is guided along the fiber.

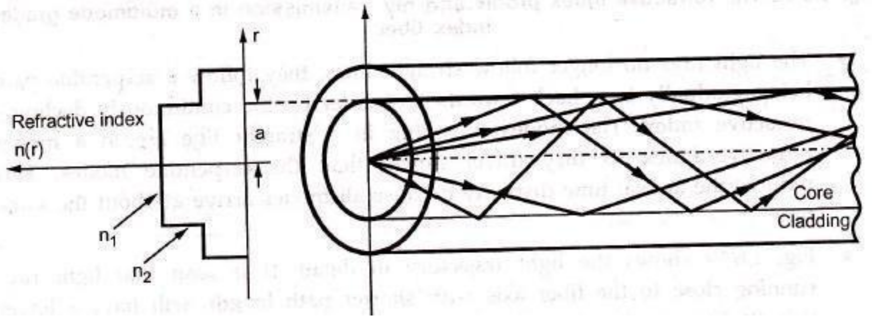


Fig.1.8 Multi-mode step index fiber

- Light rays passing through the fiber are continuously reflected off the glass cladding towards the centre of the core at different angles and lengths, limiting overall bandwidth.

- The disadvantage of multimode step index fibers is that the different optical lengths caused by various angles at which light is propagated relative to the core, causes the transmission bandwidth to be fairly small. Because of these limitations, multimode step index fiber is typically only used in applications requiring distances of less than 1 km.

Multimode Graded Index Fiber

- The core size of multimode graded index fiber cable is varying from 50 to 100 μm range. The light ray is propagated through the refraction. The light ray enters the fiber at many different angles. As the light propagates across the core toward the center it is intersecting a less dense to more dense medium. Therefore the light rays are being constantly being refracted and ray is bending continuously. This cable is mostly used for long distance communication.
- The light rays no longer follow straight lines, they follow a serpentine path being gradually bent back towards the center by the continuously declining refractive index. The modes travelling in a straight line are in a higher refractive index so they travel slower than the serpentine modes. This reduces the arrival time disparity because all modes arrive at about the same time.

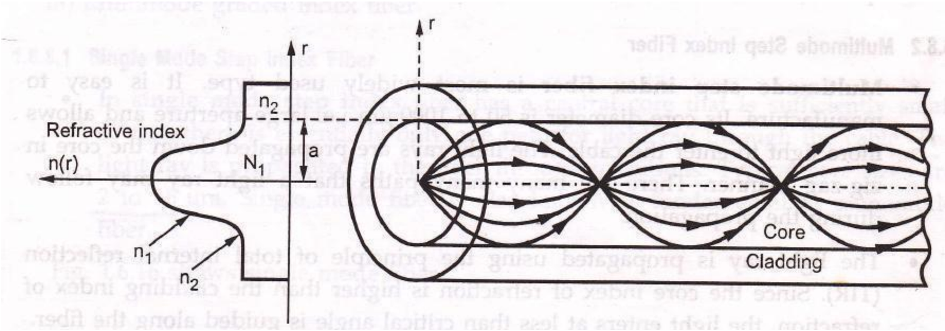


Fig.1.9 multi-mode graded index fiber

Transmission Characteristics of Optical Fibers

One of the important property of optical fiber is signal attenuation. It is also known as fiber loss or signal loss. The signal attenuation of fiber determines the maximum distance between transmitter and receiver. The attenuation also determines the number of repeaters required, maintaining repeater is a costly affair. Another important property of optical fiber is distortion mechanism. As the signal pulse travels along the fiber length it becomes broader. After sufficient length the broad pulses starts overlapping with adjacent pulses. This creates error in the receiver. Hence the distortion limits the information carrying capacity of fiber.

Attenuation

- Attenuation is a measure of decay of signal strength or loss of light power that
- occurs as light pulses propagate through the length of the fiber.
- In optical fibers the attenuation is mainly caused by two physical factors absorption and scattering losses. Absorption is because of fiber material and scattering due to structural imperfection within the fiber. Nearly 90 % of total attenuation is caused by Rayleigh scattering only. Microbending of optical fiber also contributes to the attenuation of signal.
- The rate at which light is absorbed is dependent on the wavelength of the light and the characteristics of particular glass. Glass is a silicon compound, by adding different additional chemicals to the basic silicon dioxide the optical properties of the glass can be changed.
- The Rayleigh scattering is wavelength dependent and reduces rapidly as the wavelength of the incident radiation increases.

Attenuation Units

As attenuation leads to a loss of power along the fiber, the output power is significantly less than the couples power. Let the couples optical power is p(0) i.e. at origin (z = 0).

Then the power at distance z is given by,

$$P(z) = P(0)e^{-\alpha_p z}$$

where, αp is fiber attenuation constant (per km).

$$\propto_p = \frac{1}{z} \ln \left[\frac{P(0)}{P(z)}\right]$$

$$\boxed{\propto_{dB/km} = 10.\frac{1}{z} \log \left[\frac{P(0)}{P(z)}\right]}$$

$$\propto_{dB/km} = 4.343 \ \propto_p \ \text{per km}$$

Absorption

Absorption loss is related to the material composition and fabrication process of fiber. Absorption loss results in dissipation of some optical power as hear in the fiber cable. Although glass fibers are extremely pure, some impurities still remain as residue after purification. The amount of absorption by these impurities depends on their concentration and light wavelength.

Absorption is caused by three different mechanisms.

- Absorption by atomtic defects in glass composition.
- Extrinsic absorption by impurity atoms in glass matts.
- Intrinsic absorption by basic constituent atom of fiber.

Absorption by Atomic Defects

Atomic defects are imperfections in the atomic structure of the fiber materials such as missing molecules, high density clusters of atom groups. These absorption losses are negligible compared with intrinsic and extrinsic losses.

The absorption effect is most significant when fiber is exposed to ionizing radiation in nuclear reactor, medical therapies, space missions etc. The radiation dames the internal structure of fiber. The damages are proportional to the intensity of ionizing particles. This results in increasing attenuation due to atomic defects and absorbing optical energy. The total dose a material receives is expressed in rad (Si), this is the unit for measuring radiation absorbed in bulk silicon.

1 rad (Si) = 0.01 J.kg

Extrinsic Absorption

Extrinsic absorption occurs due to electronic transitions between the energy level and because of charge transitions from one ion to another. A major source of attenuation is from transition of metal impurity ions such as iron, chromium, cobalt and copper. These losses can be upto 1 to 10 dB/km. The effect of metallic impurities can be reduced by glass refining techniques.

Intrinsic Absorption

Intrinsic absorption occurs when material is in absolutely pure state, no density variation and in homogeneities. Thus intrinsic absorption sets the fundamental lower limit on absorption for any particular material. Intrinsic absorption results from electronic absorption bands in UV region and from atomic vibration bands in the near infrared region.

The electronic absorption bands are associated with the band gaps of amorphous glass materials. Absorption occurs when a photon interacts with an electron in the valence band and excites it to a higher energy level. UV absorption decays exponentially with increasing wavelength (λ).

Scattering Losses

Scattering losses exists in optical fibers because of microscopic variations in the material density and composition. As glass is composed by randomly connected network of molecules and several oxides (e.g. SiO2, GeO2 and P2O5), these are the major cause of compositional structure fluctuation. These two effects results to variation in refractive index and Rayleigh type scattering of light.

Rayleigh scattering

Rayleigh scattering of light is due to small localized changes in the refractive index of the core and cladding material. There are two causes during the manufacturing of fiber. The first is due to slight fluctuation in mixing of ingredients. The random changes because of this are impossible to eliminate completely. The other cause is slight change in density as the silica cools and solidifies.

When light ray strikes such zones it gets scattered in all directions. The amount of scatter depends on the size of the discontinuity compared with the wavelength of the light so the shortest Wave length (highest frequency) suffers most scattering. Fig. 1.10 shows graphically the Relationship between wavelength and Rayleigh scattering loss.

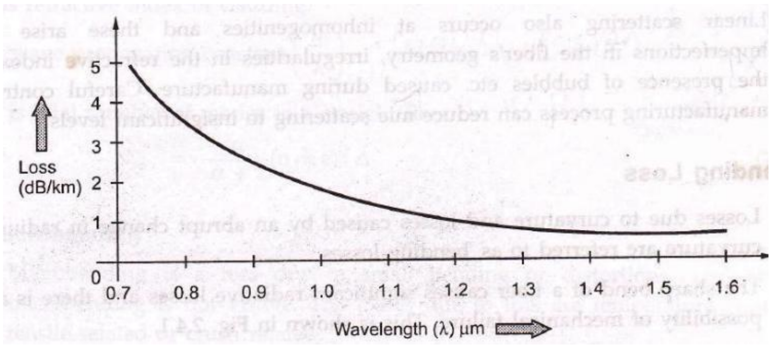


Fig.1.10 scattering losses

Scattering loss for single component glass is given by,

$$\propto_{scat} = \frac{8\pi^3}{3\lambda^4}\,(n^2-1)^2\, k_B\, T_f\, \beta_T \text{ nepers}$$

where, n = Refractive index

k_B = Boltzmann's constant

β_T = Isothermal compressibility of material

T_f = Temperature at which density fluctuations are frozen into the glass as it solidifies (fictive temperature)

Multimode fibers have higher dopant concentrations and greater compositional fluctuations. The overall losses in this fibers are more as compared to single mode fibers.

Mie Scattering

Linear scattering also occurs at in homogenities and these arise from imperfections in the fiber's geometry, irregularities in the refractive index and the presence of bubbles etc. caused during manufacture. Careful control of manufacturing process can reduce mie scattering to insignificant levels.

Bending Loss

There are two types of bends in optical fibers.

(a) Macroscopic loss (having larger radii than that of the fiber diameter)

(b) Microscopic loss (random microscopic bends of the fiber axis)

Macro bending Loss

For slight bends, the loss is extremely small and is not observed. As the radius of curvature decreases, the loss increases exponentially until at a certain critical radius of curvature loss becomes observable. If the bend radius is made a bit smaller once this threshold point has been reached, the losses suddenly become extremely large. It is known that any bound core mode has an evanescent field tail in the cladding which decays exponentially as a function of distance from the core. Since this field tail moves along with the field in the core, part of the energy of a propagating mode travels in the fiber cladding. When a fiber is bent, the field tail on the far side of the centre of curvature must move faster to keep up with the field in the core, for the lowest order fiber mode.

Micro bending Loss

Another form of radiation loss in optical waveguide results from mode coupling caused by random micro bends of the optical fiber. Micro bends are repetitive small scale fluctuations in the radius of curvature of the fiber axis. They are caused either by non-uniformities in the manufacturing of the fiber or by non-uniform lateral pressures created during the cabling of the fiber. An increase in attenuation results from micro bending because the fiber curvature causes repetitive coupling of energy between the guided modes and the leaky or non-guided modes in the fiber.

Micro bending losses can be minimized by placing a compressible jacket over the fiber. When external forces are applied to this configuration, the jacket will be deformed but the fiber will tend to stay relatively straight.

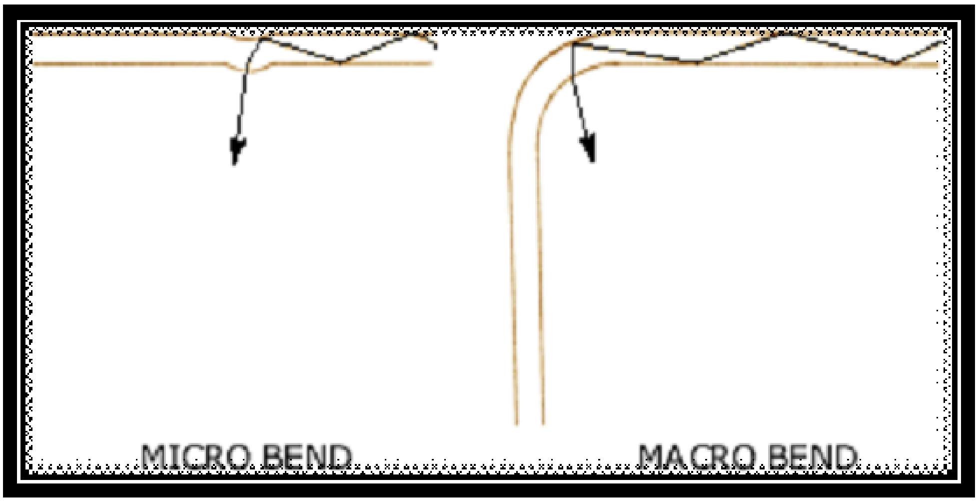


Fig.1.11 bending losses

Core and Cladding Loss

Since the core and cladding have different indices of refraction hence they have different Attenuation coefficients α1 and α2 respectively.

For step index fiber, the loss for a mode order (v, m) is given by,

$$\propto_{v\,m} = \propto_1 \frac{P_{core}}{P} + \propto_2 \frac{P_{cladding}}{P}$$

For low-order modes, the expression reduced to

$$\propto_{v\,m} = \propto_1 + (\propto_2 + \propto_1) \frac{P_{cladding}}{P}$$

where, $\frac{P_{core}}{P}$ and $\frac{P_{cladding}}{P}$ are fractional powers.

For graded index fiber, loss at radial distance is expressed as,

$$\propto(r) = \propto_1 + (\propto_2 - \propto_1) \frac{n^2(0) - n^2(r)}{n^2(0) - n_2^2}$$

The loss for a given mode is expressed by,

$$\propto_{Graded\ Index} = \frac{\int_0^\infty \propto(r)\, P(r)\, r\, dr}{\int_0^\infty P(r)\, r\, dr}$$

where, P(r) is power density of that model at radial distance r.

Signal Distortion in Optical Waveguide

The pulse gets distorted as it travels along the fiber lengths. Pulse spreading in fiber is referred as dispersion. Dispersion is caused by difference in the propagation times of light rays that takes different paths during the propagation. The light pulses travelling down the fiber encounter dispersion effect because of this the pulse spreads out in time domain.

Dispersion limits the information bandwidth. The distortion effects can be analyzed by studying the group velocities in guided modes.

Information Capacity Determination

- Dispersion and attenuation of pulse travelling along the fiber is shown in Fig. 1.12

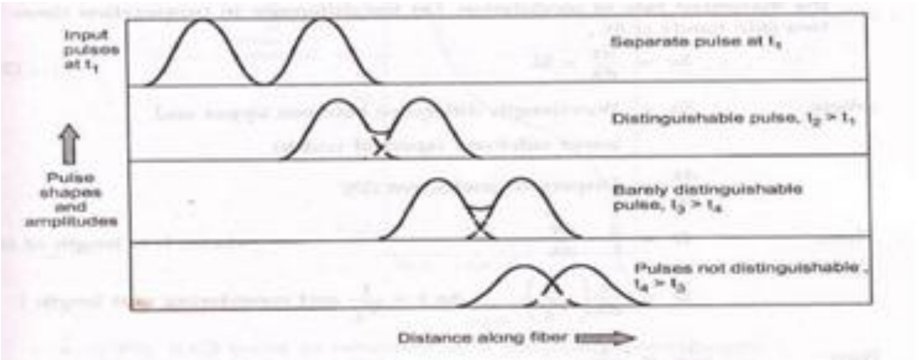


Fig.1.12 dispersion

Fig. 1.12 shows, after travelling some distance, pulse starts broadening and overlap with the neighbouring pulses. At certain distance the pulses are not even distinguishable and error will occur at receiver. Therefore the information capacity is specified by bandwidth-distance product (MHz km). For step index bandwidth distance product is 20 MHz km and for graded index it is 2.5 MHz .km.

Group Delay

Consider a fiber cable carrying optical signal equally with various modes and each mode contains all the spectral components in the wavelength band. All the spectral components travel independently and they observe different time delay and group delay in the direction of propagation. The velocity at which the energy in a pulse travels along the fiber is known as group velocity. Group velocity is given by,

$$V_g = \frac{\partial w}{\partial \beta}$$

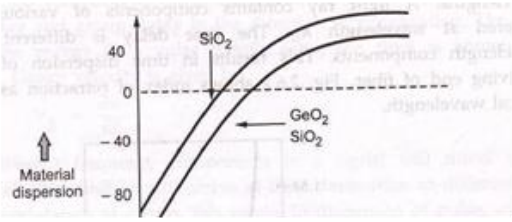
Intermodal dispersion

Also known as ‘chromatic dispersion’ or ‘group velocity dispersion’ (GVD).

When an EM wave travels through a medium of RI, ‘n’ the speed of wave is reduced from speed of light.That is, v = c/n.

Hence the speed of light in a material depends on its RI which in turn is a frequency dependent parameter. As a result different spectral components of the light pulse travels at slightly different group velocities which causes group velocity dispersion or chromatic dispersion.

$$\delta\tau = \frac{d\tau}{d\lambda}\ x\ \delta\lambda$$



$$\frac{d\tau}{d\lambda}$$

$$\mathrm{D} = \frac{1}{\mathrm{L}}.\frac{d\tau}{d\lambda}$$

$$\mathrm{D} = \frac{d}{d\lambda}\left(\frac{1}{V_g}\right) \qquad \text{As } \tau = \frac{1}{V_g}$$

$$\frac{1}{V_g} = \frac{d\beta}{d\omega}$$

$$\frac{1}{V_g} = \frac{d\lambda}{d\omega}\mathrm{x}\frac{d\beta}{d\lambda}$$

$$\frac{1}{V_g} = \frac{-\lambda^2}{2\pi c}\mathrm{x}\frac{d\beta}{d\lambda}$$

$$\mathrm{D} = \frac{d}{d\lambda}\left(\frac{-\lambda^2}{2\pi\, c}.\frac{d\beta}{d\lambda}\right)$$

UNIT-II

Fiber Optical Sources and Coupling

Optical Sources

Optical transmitter coverts electrical input signal into corresponding optical signal. The optical signal is then launched into the fiber. Optical source is the major component in an optical transmitter. Popularly used optical transmitters are Light Emitting Diode (LED) and semiconductor Laser Diodes (LD).

Direct and indirect Band gap materials

Direct Band gap materials

In direct band gap semiconductor, the bottom of the conduction band and top of the valence band lies at the same value of K. In this, electron can directly excite or de-excite by the absorption or emission of photon and there is no phonon involvement in the process of excitation and de-excitation.

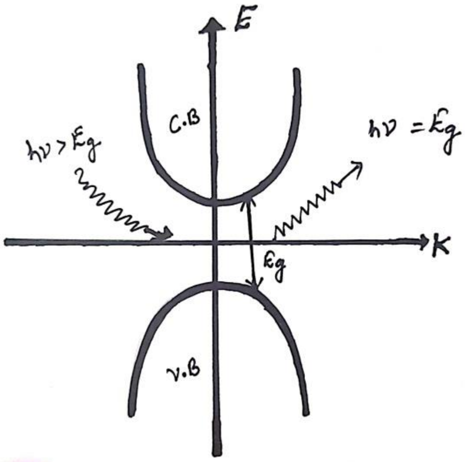


Fig.2.1 Direct band gap

If a photon incident of energy, hv>Eg, there is absorption then electron of valence band will absorb this energy and excite to the conduction band and when it de-excite to valence band, then it will emit some energy i.e. hv=Eg.

There is no requirement of phonon or lattice in the conservation of energy and momentum. Direct bandgap semiconductors are used in light-emitting applications like LED and LASER. Ex. GaAs, CdS, ZnS, CdSe etc.

In Direct Band gap materials

In Indirect bandgap semiconductor, top of the valence band and bottom of the conduction band lies at different values of K. If an electron goes from the top of the valence band to the bottom of the conduction band, it has to change its energy as well as wave-vector K.

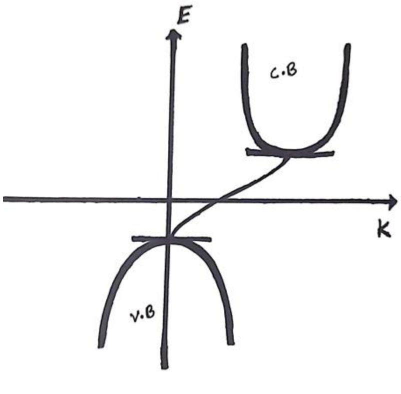


Fig.2.2 indirect band

For momentum and energy conservation, there is the involvement of phonon in the conservation process. If there is de-excitation of the electron, then not all the energy will be emitted in the form of the photon but some energy is emitted in the form of phonons i.e. some part is transferred to the lattice, and the lattice will vibrate and generate heat. So indirect bandgap semiconductor bandgap semiconductor is not suitable for light emission. Ex. Si, Ge, GaP SiC, etc.

Light Emitting Diodes(LEDs)

p-n Junction

Conventional p-n junction is called as homojunction as same semiconductor material is sued on both sides junction. The electron-hole recombination occurs in relatively layer = 10 μm. As the carriers are not confined to the immediate vicinity of junction, hence high current densities can not be realized.

The carrier confinement problem can be resolved by sandwiching a thin layer (= 0.1 m) between p-type and n-type layers. The middle layer may or may not be doped. The carrier confinement occurs due to bandgap discontinuity of the junction. Such a junction is call heterojunction and the device is called double heterostructure.

In any optical communication system when the requirements is

1. Bit rate f 100-2—Mb/sec.
2. Optical power in tens of micro watts.

LEDs are best suitable optical source.

LED Structures

Heterojuncitons

A heterojunction is an interface between two adjoining single crystal semiconductors with different bandgap. Heterojuctions are of two types, Isotype (n-n or p-p) or Antisotype (p-n).

Double Heterojunctions (DH)

In order to achieve efficient confinement of emitted radiation double heterojunctions re used in LED structure. A heterojunciton is a junction formed by dissimilar semiconductors. Double heterojunction (DH) is formed by two different semiconductors on each side of active region. Fig. 3.3 shows double heterojunction (DH) light emitter.

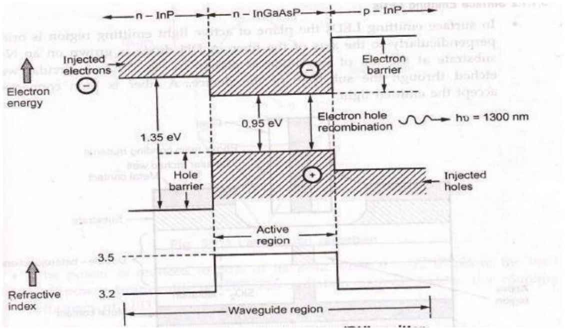


Fig.2.3 double heterojunction (DH) light emitter

- The crosshatched regions represent the energy levels of freecharge. Recombination occurs only in active InGaAsP layer. The two materials have different bandgap energies and different refractive indices. The changes in bandgap energies create potential barrier for both holes and electrons. The free charges can recombine only in narrow, well defined active layer side.
- A double heterjuction (DH) structure will confine both hole and electrons to a narrow active layer. Under forward bias, there will be a large number of carriers injected into active region where they are efficiently confined. Carrier recombination occurs in small active region so leading to an efficient device. Antoer advantage DH structure is that the active region has a higher refractive index than the materials on either side,

hence light emission occurs in an optical waveguide, which serves to narrow the output beam.

LED configurations

At present there are two main types of LED used in optical fiber links

Surface emitting LED.

Edge emitting LED.

Surface Emitting LEDs

- In surface emitting LEDs the plane of active light emitting region is oriented perpendicularly to the
- axis of the fiber. A DH diode is grown on an N-type substrate at the top of the diode as shown in Fig. 3.1.2. A circular well is etched through the substrate of the device. A fiber is then connected to accept the emitted
- At the back of device is a gold heat sink. The current flows through the p-type material and forms the small circular active region resulting in the intense beam of light.

Diameter of circular active area = 50 μm
Thickness of circular active area = 2.5 μm
Current density = 2000 A/cm2 half-power
Emission pattern = Isotropic, 120o beamwidth.

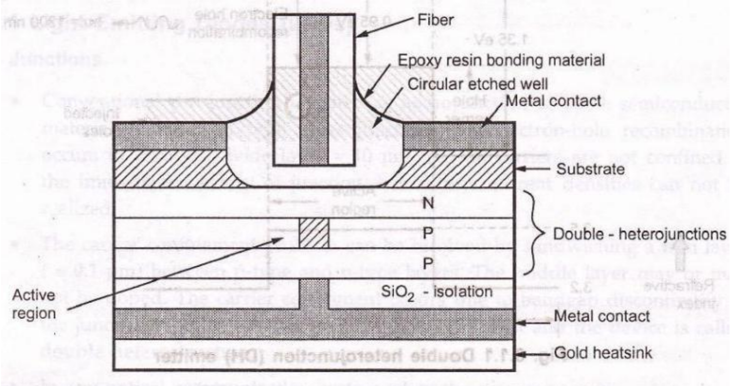


Fig.2.4 surface emitting

Edge Emitting LEDS (ELEDs)

In order to reduce the losses caused by absorption in the active layer and to make the beam more directional, the light is collected from the edge of the LED. Such a device is known as edge emitting LED or ELED.

It consists of an active junction region which is the source of incoherent light and two guiding layers. The refractive index of guiding layers is lower than active region but higher than outer surrounding material. Thus a waveguide channel is form and optical radiation is directed into the fiber.Fig.3.5 shows structure of LED

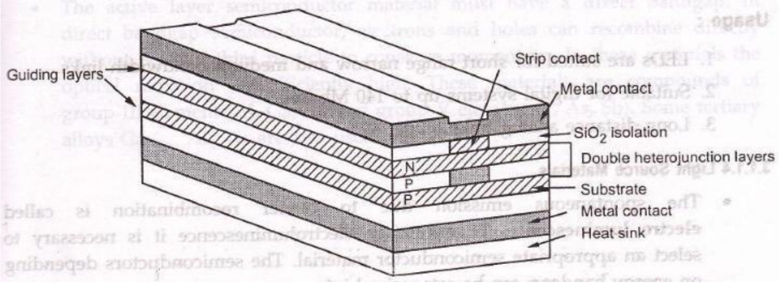


Fig.2.5 Edge emitting

Edge emitter's emission pattern is more concentrated (directional) providing improved coupling efficiency. The beam is Lambartian in the plane parallel to the junction but diverges more slowly in the plane perpendicular to the junction.

Light source materials

The spontaneous emission due to carrier recombination is called electro luminescence. To encourage electroluminescence it is necessary to select as appropriate semiconductor material. The semiconductors depending on energy band gap can be categorized into

Direct band gap semiconductor
In direct band gap semiconductor

Direct band gap semiconductors are most useful for this purpose. In direct band gap semiconductors the electrons and holes on either side of band gap have same value of crystal momentum. Hence direct recombination is possible. The recombination occurs within 10-8 to 10-10 sec.

The active layer semiconductor material must have a direct band gap. In direct band gap semiconductor, electrons and holes can recombine directly without need of third particle to conserve momentum. In these materials the optical radiation is sufficiently high. These materials are compounds of group III elements (Al, Ga, In) and group V element (P, As, Sb).

Quantum efficiency and LED power

- The internal quantum efficiency (η_{int}) is defined as the ratio of radiative recombination rate to the total recombination rate.

$$\eta_{int} = \frac{R_r}{R_r + R_{nr}}$$

Where,
R_r is radiative recombination rate.
R_{nr} is non-radiative recombination rate.
If n are the excess carriers, then radiative life time, $\Gamma r = n/Rr$ and
non-radiative life time, $\Gamma r = n/Rnr$

Optical power generated internally in LED is given as

$$P_{int} = R_r.h\ v$$

$$P_{int} = \left(\eta_{int}\ x\ \frac{I}{q}\right).h\ v$$

$$\boxed{P_{int} = \eta_{int}.\frac{hc\ I}{q\lambda}}$$

Not all internally generated photons will available from output of device. The external quantum efficiency is used to calculate the emitted power. The external quantum efficiency is defined as the ratio of photons emitted from LED to the number of photons generated internally. It is given by equation

$$\eta_{ext} = \frac{1}{n(n+1)^2}$$

The optical output power emitted from LED is given as

$$\boxed{P = \frac{1}{n\ (n+1)^2}.P_{int}}$$

Modulation of a LED

The light output from an LED has a region where it is linearly proportional to the forward current through the diode, it is useful for producing a light level which is proportional to some signal. That signal can then be send through a fiber optic cable and detected on the other end. The basic need for modulation is then a device which produces a

$$P_{int} = R_r.h\ v$$

current proportional to the input voltage of the applied signal. This can be done with an op-amp arranged as a voltage-to-current converter.

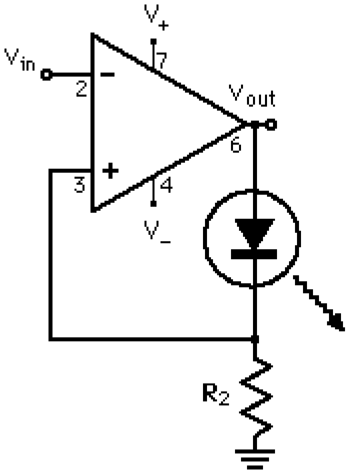


Fig.2.6 modulation of led

Laser diode

Laser diode is an improved LED, in the sense that uses stimulated emission in semiconductor from optical transitions between distribution energy states of the valence and conduction bands with optical resonator structure such as Fabry-Perot resonator with both optical and carrier confinements.

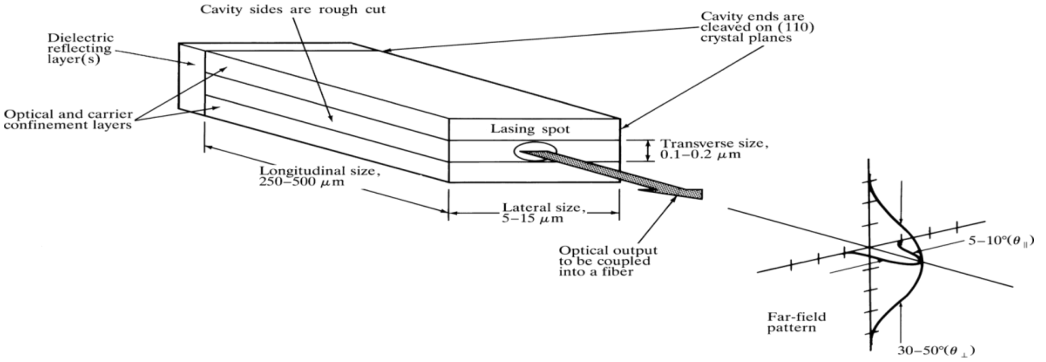


Fig.2.7 fabry resonator

Threshold condition

To determine the lasing condition and resonant frequencies, we should focus on the optical wave propagation along the longitudinal direction, z-axis. The optical field intensity, I, can be written as:

$$I(z,t) = I(z)e^{j(\omega t - \beta z)}$$

Lasing is the condition at which light amplification becomes possible by virtue of population inversion. Then, stimulated emission rate into a given EM mode is proportional to the intensity of the optical radiation in that mode.

$$G_{th} = \beta j_{th}$$

Rate equations

The laser diode rate equations model the electrical and optical performance of a laser diode. This system of ordinary differential equations relates the number or density of photons and charge carriers (electrons) in the device to the injection current and to device and material parameters such as carrier lifetime, photon lifetime, and the optical gain.

The rate equations may be solved by numerical integration to obtain a time-domain solution, or used to derive a set of steady state or small signal equations to help in further understanding the static and dynamic characteristics of semiconductor lasers.

The laser diode rate equations can be formulated with more or less complexity to model different aspects of laser diode behavior with varying accuracy.

In the multimode formulation, the rate equations model a laser with multiple optical modes. This formulation requires one equation for the carrier density, and one equation for the photon density in each of the optical cavity modes:

$$\frac{dN}{dt} = \frac{I}{eV} - \frac{N}{\tau_n} - \sum_{\mu=1}^{\mu=M} G_\mu P_\mu$$

$$\frac{dP_\mu}{dt} = \Gamma_\mu (G_\mu - \frac{1}{\tau_p}) P_\mu + \beta_\mu \frac{N}{\tau_n}$$

where:

M is the number of modes modeled, μ is the mode number, and subscript μ has been added to G, Γ, and β to indicate these properties may vary for the different modes.

External Quantum efficiency

The external quantum efficiency is defined as the number of photons emitted per electron hole pair recombination above threshold point. The external quantum efficiency η_{ext} is given by

$\eta_{ext} = \eta_i (g_{th} - \alpha)/g_{th}$

where, ηi = Internal quantum efficiency (0.6-0.7).

gth = Threshold gain.

α = Absorption coefficient

Typical value of ηext for standard semiconductor laser is ranging between 15-20 %.

Resonant Frequencies

At threshold lasing

$2\beta L = 2\pi m$

where, (propagation constant) m is an integer.

$M = 2L (n/\lambda)$

Since $c = v\lambda$

Gain in any laser is a function of frequency. For a Gaussian output the gain and frequency are related by expression

$$g(\lambda) = g(0)e^{\left[-\frac{(\lambda-\lambda_0)^2}{2\sigma^2}\right]}$$

where, g(0) is maximum gain. λ0 is center wavelength in spectrum.is spectral width of the gain. The frequency spacing between the two successive modes is

$$\boxed{\Delta v = \frac{c}{2Ln}}$$

$$\boxed{\Delta\lambda = \frac{\lambda^2}{2Ln}}$$

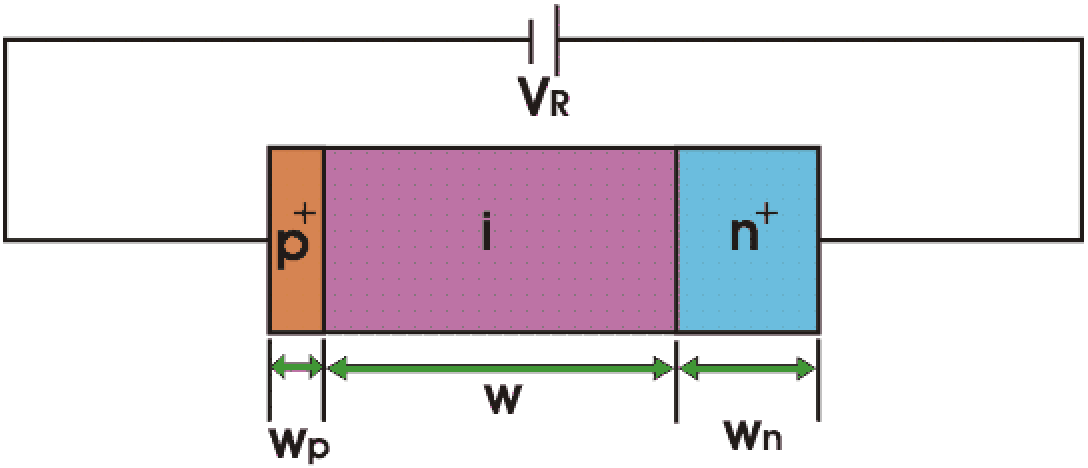
Temperature effects

Due to fiber optics sending light beams down the thin strands of glass rather than electrical signals, these cables are not affected by weather changes. Rain, cold and extreme heat can affect traditional electrical signals but **do not have any affect on fiber optics**.

UNIT-III
Fiber Optical Receivers

PHOTODETECTORS:

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.

Operation: 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 (r_N and r_P). The lifetime and the diffusion length are related as:

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

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

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

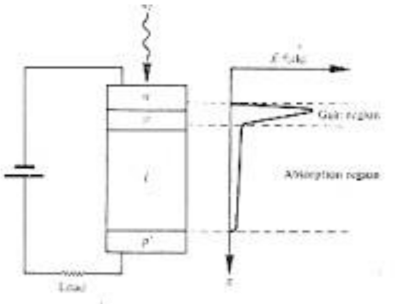
$$\eta = \frac{No.of\ electron\text{–}hole\ pair\ generated}{No.of\ incident\ photons}$$

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

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:

$$\boldsymbol{M} = \frac{\boldsymbol{IM}}{\boldsymbol{IP}}$$

I_M: Multiplied carrier current

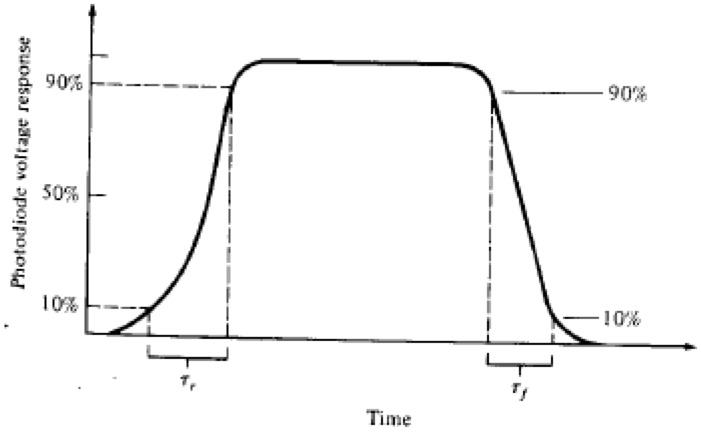
I_P: Primary current

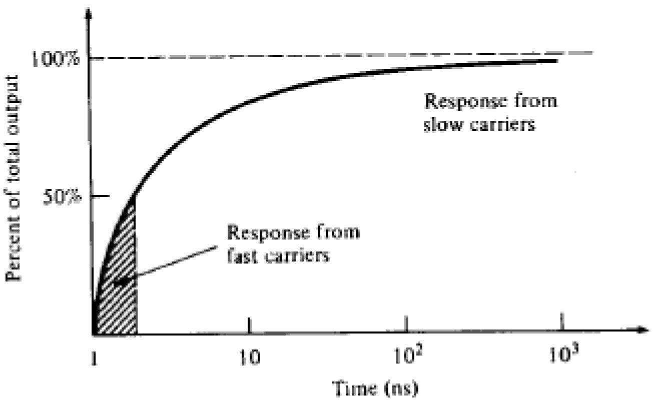
DETECTOR RESPONSE TIME: The response time of a photodiode together with its output circuit depends upon, a). The transit time of the photo carriers in the depletion region. b). The diffusion time of the photo carriers generated outside the depletion region. c). The RC time constant of the photodiode.

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’.

$$\boldsymbol{t}_d = \frac{m}{\boldsymbol{vd}}$$

The photodiode response time to an optical input pulse is

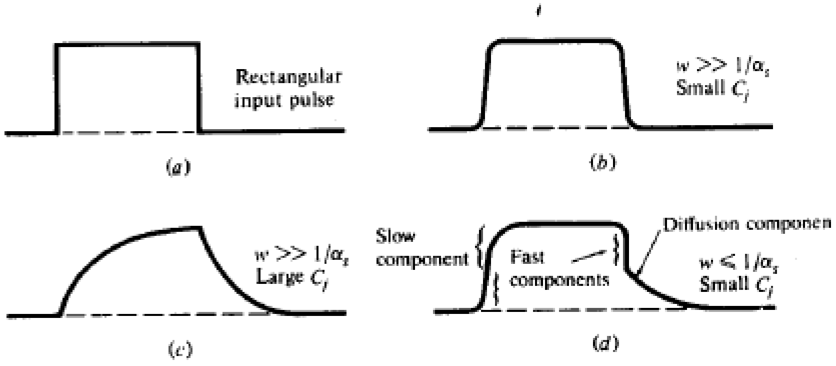




r_r: Rise time life time
r_f : fall time life time
Junction capacitances:

$C_j = \frac{\in sA}{W}$

Now, photodiode pulse responses under various detector parameters:

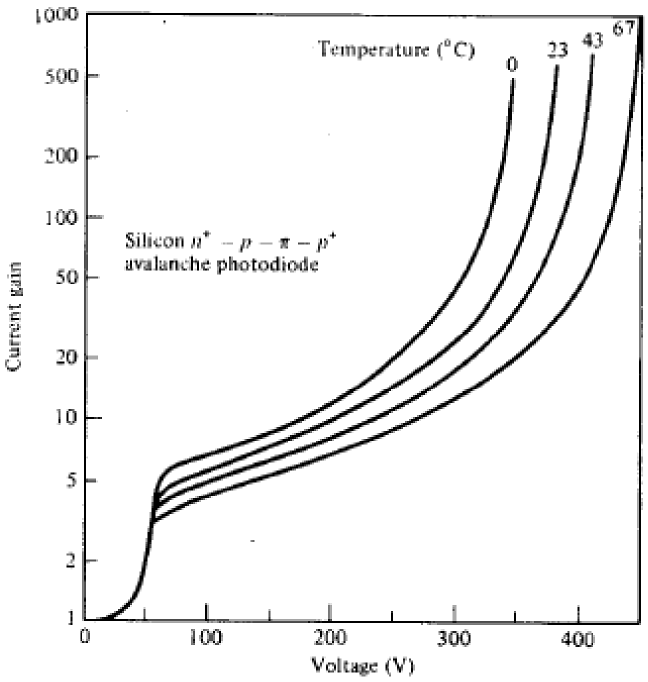


TEMPERATURE EFFECT ON AVALANCHE GAIN: The gain mechanism of an avalanche photodiode is very temperature sensitive because of the dependence of the electron and hole ionization rates. This temperature dependence is particular critical at highbias voltage, where small changes in temperature can cause large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

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



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

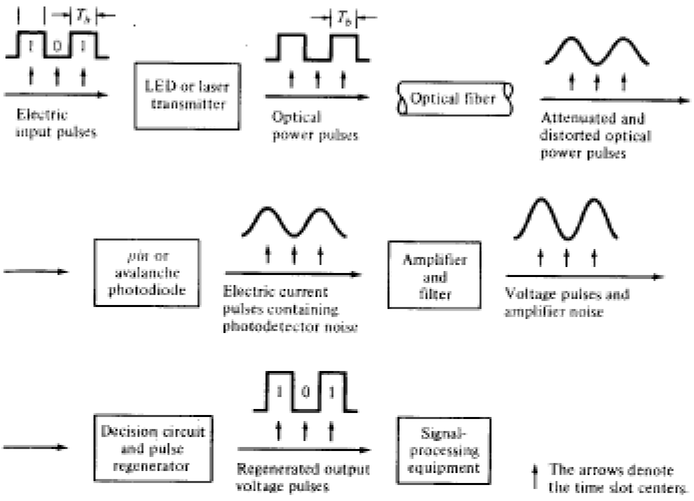
So, the breakdown voltage:

$\boldsymbol{V_B = V_B(T_0)[1 + a(T - T_0)]}$

OPTICAL RECEIVER OPERATION:

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 versionof this distorted signal.

DIGITAL SIGNAL TRANSMISSION:

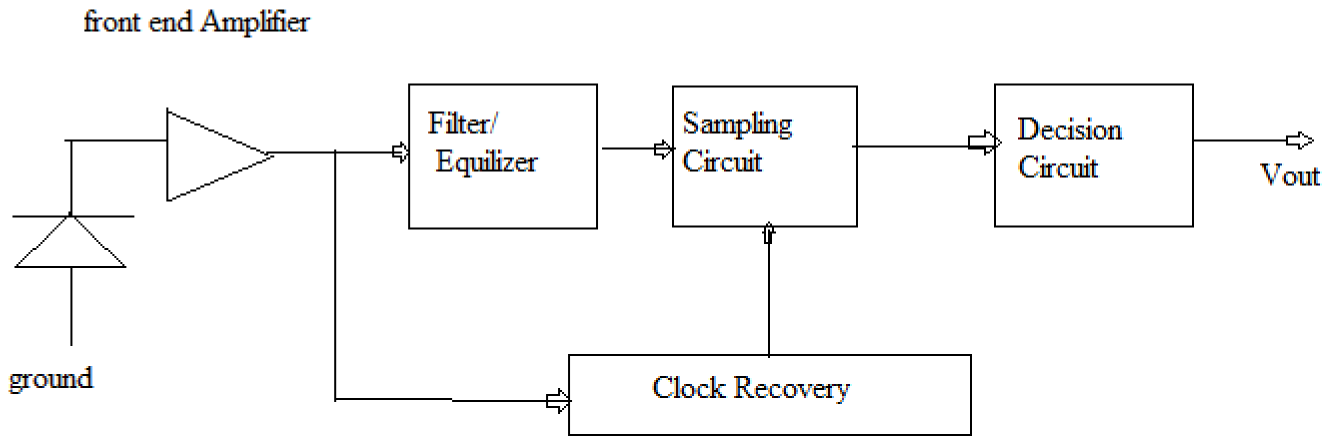


The transmitted signal is a two level binary data stream consisting of either a 0 or a 1 in a time slot of duration T_b. This time slot is referred to as a bit period. One technique for sending binary data is amplitude shift keying (ASK) or on-off key (OOK). The resultant signal wave thus consists of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

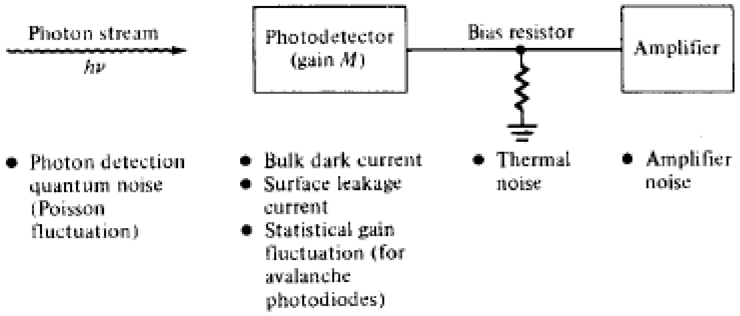


As per the diagram, the first element is either a pin or an avalanche photodiode, which produces an electric current that is proportional to the received power level. Since this electric current is typically very weak, a front end amplifier boosts it to a level that can be used by the following electronics. 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 :

$$\bar{N} = \frac{y}{h\nu}\int_{0}^{C} P(t)\,dt = \frac{yE}{h\nu}$$

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:

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

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 VOUT(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).

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

where, N_e: error occurring in a certain time interval τ

N_t: Pulse transmitted during this interval

B: Bit rate $= \frac{1}{Tb}$

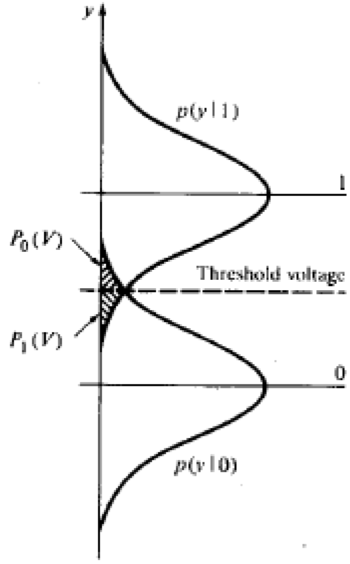
In telecommunication, the error rate depends upon the SNR (Range 10^{-9} to 10^{-12}). The system error rate requirement and the receiver noise levels set a lower limit on the optical signal power level that is required at the photo detector.

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:

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

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:

$$P_{sensitivity} = \frac{P1}{\ } = J1/2RM$$

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 :

$$\sigma_T^2 = \frac{4RBT}{RL} \frac{B}{2} fn$$

After substituting the operating values, R_L=200Ω, T=300^0K, f_n=3dB, $\sigma_T=9.10\times10^{-12}B^{1/2}$, BER=10

$$\boldsymbol{P_{sensitivity}} = \frac{7.37}{M}[\boldsymbol{5.6 \times 10^{-19} MF(M)B} + \boldsymbol{9.10 \times 10^{-12} B^{1/2}}]$$

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:

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

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 outpu

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

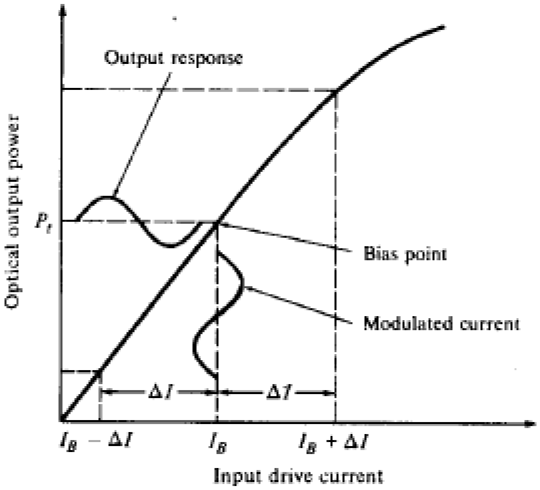
$$\langle i_s^2 \rangle = \frac{1}{2}(MmI_p)^2$$

and the mean square noise current is:

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

For SNR,

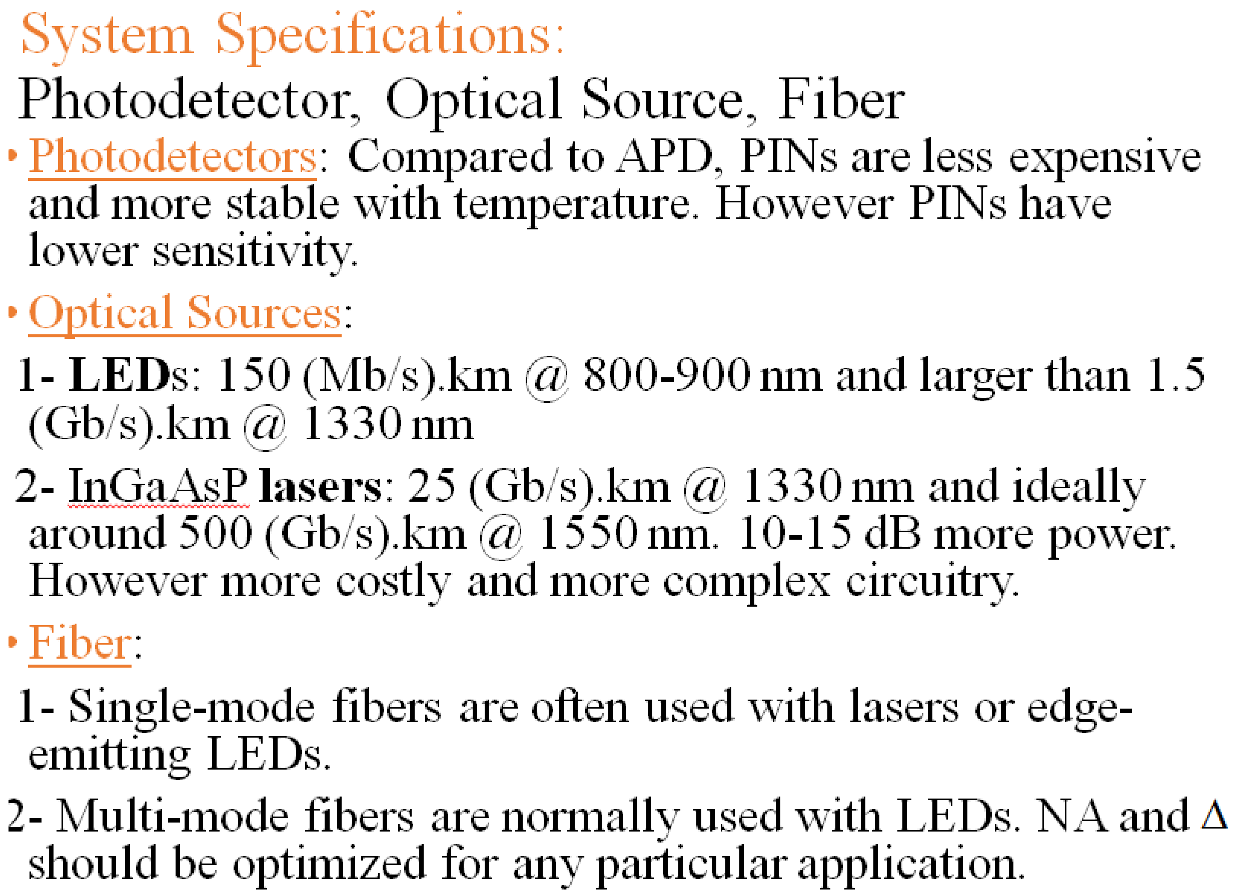
$$\frac{S}{N} = \frac{\langle i_s^2 \rangle}{\langle i_N^2 \rangle} = \frac{m^2 I_P}{4qBe} = \frac{m^2 RP_r}{4qBe}$$



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

UNIT IV

OPTICAL FIBER SYSTEM DESIGN & TECHNOLOGY



System Specifications:

Photodetector, Optical Source, Fiber

- Photodetectors: Compared to APD, PINs are less expensive and more stable with temperature. However PINs have lower sensitivity.
- Optical Sources:

1- **LED**s: 150 (Mb/s).km @ 800-900 nm and larger than 1.5 (Gb/s).km @ 1330 nm

2- InGaAsP **lasers**: 25 (Gb/s).km @ 1330 nm and ideally around 500 (Gb/s).km @ 1550 nm. 10-15 dB more power. However more costly and more complex circuitry.

- Fiber:

1- Single-mode fibers are often used with lasers or edge-emitting LEDs.

2- Multi-mode fibers are normally used with LEDs. NA and Δ should be optimized for any particular application.

Point-to-Point Links:-

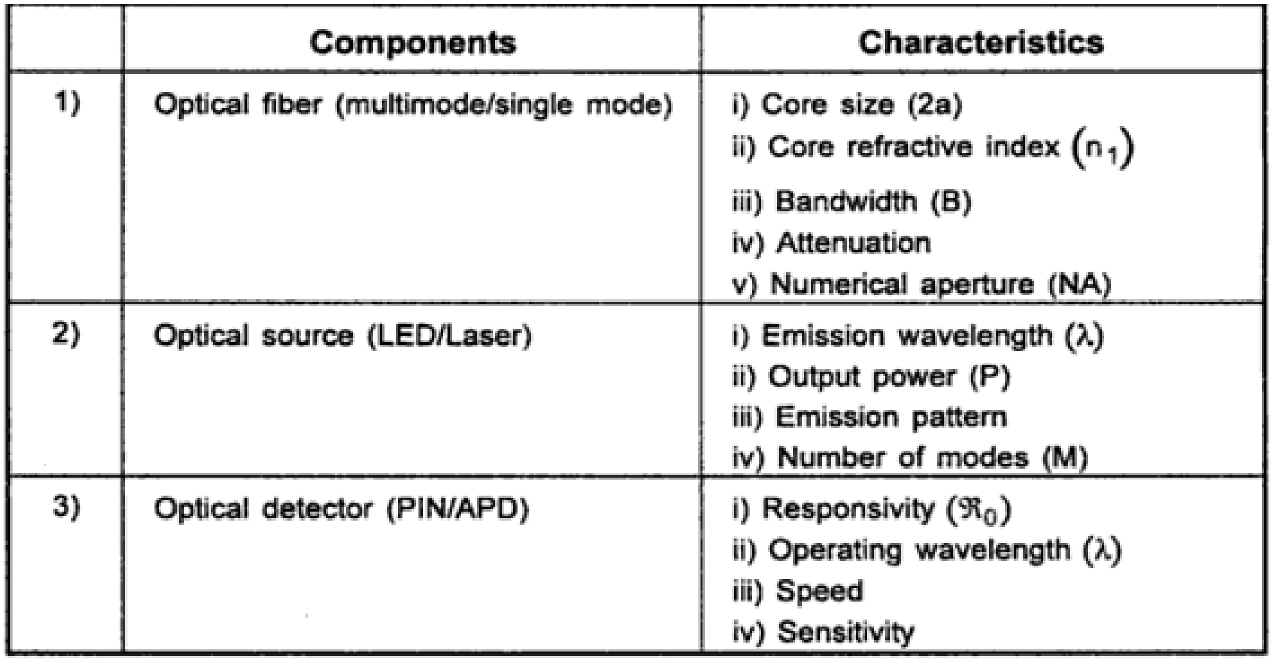
A point-to-point link comprises of one transmitter and a receiver system. This is the simplest form of optical communication link and it sets the basis for examining complex optical communication links. For analyzing the performance of any link following important aspects are to be considered.

a) Distance of transmission

b) Channel data rate

c) Bit-error rate

All above parameters of transmission link are associated with the characteristics of various devices employed in the link. Important components and their characteristics are listed below.



	Components	Characteristics
1)	Optical fiber (multimode/single mode)	i) Core size (2a) ii) Core refractive index (n_1) iii) Bandwidth (B) iv) Attenuation v) Numerical aperture (NA)
2)	Optical source (LED/Laser)	i) Emission wavelength (λ) ii) Output power (P) iii) Emission pattern iv) Number of modes (M)
3)	Optical detector (PIN/APD)	i) Responsivity ($\Re_0$) ii) Operating wavelength (λ) iii) Speed iv) Sensitivity

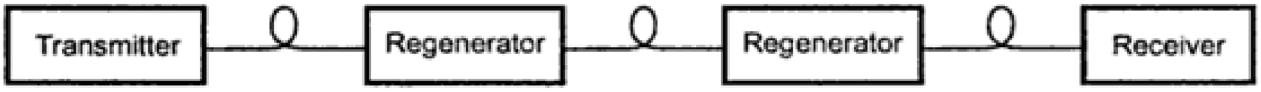


Fig.4.1 Point-to-Point Fiber links

When the link length extends between 20 to 100 km, losses associated with fiber cable increases. In order to compensate the losses optical amplifier and regenerators are used over the span of fiber cable. A regenerator is a receiver and transmitter pair which detects incoming optical signal, recovers the bit stream electrically and again convert back into optical from by modulating an optical source. An optical amplifier amplify the optical bit stream without converting it into electrical form.

The spacing between two repeater or optical amplifier is called as repeater spacing(L). The repeater spacing L depends on bit rate B. The bit rate-distance product(BL) is a measure of system performance for point-to-point links. Two important analysis for deciding performance of any fiber link are –

i) Link power budget / Power budget

ii) Rise time budget / Bandwidth budget

The Link power budget analysis is used to determine whether the receiver has sufficient power to achieve the desired signal quality. The power at receiver is the transmitted power minus link losses.

The components in the link must be switched fast enough and the fiber dispersion must be low enough to meet the bandwidth requirements of the application. Adequate bandwidth for a system can be assured by developing a rise time budget.

Link Power Budget :-

For optiming link power budget an optical power loss model is to be studied as shown in Fig.

Let lc denotes the losses occur at connector.

Lsp denotes the losses occur at splices.

αf denotes the losses occur in fiber.

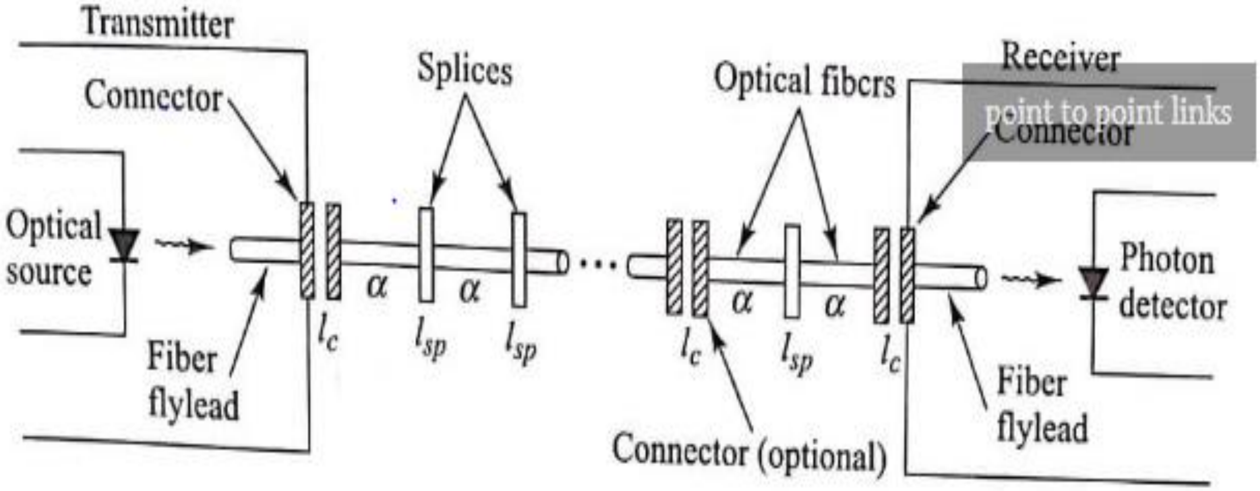


Fig.4.2 Optical Power loss Model

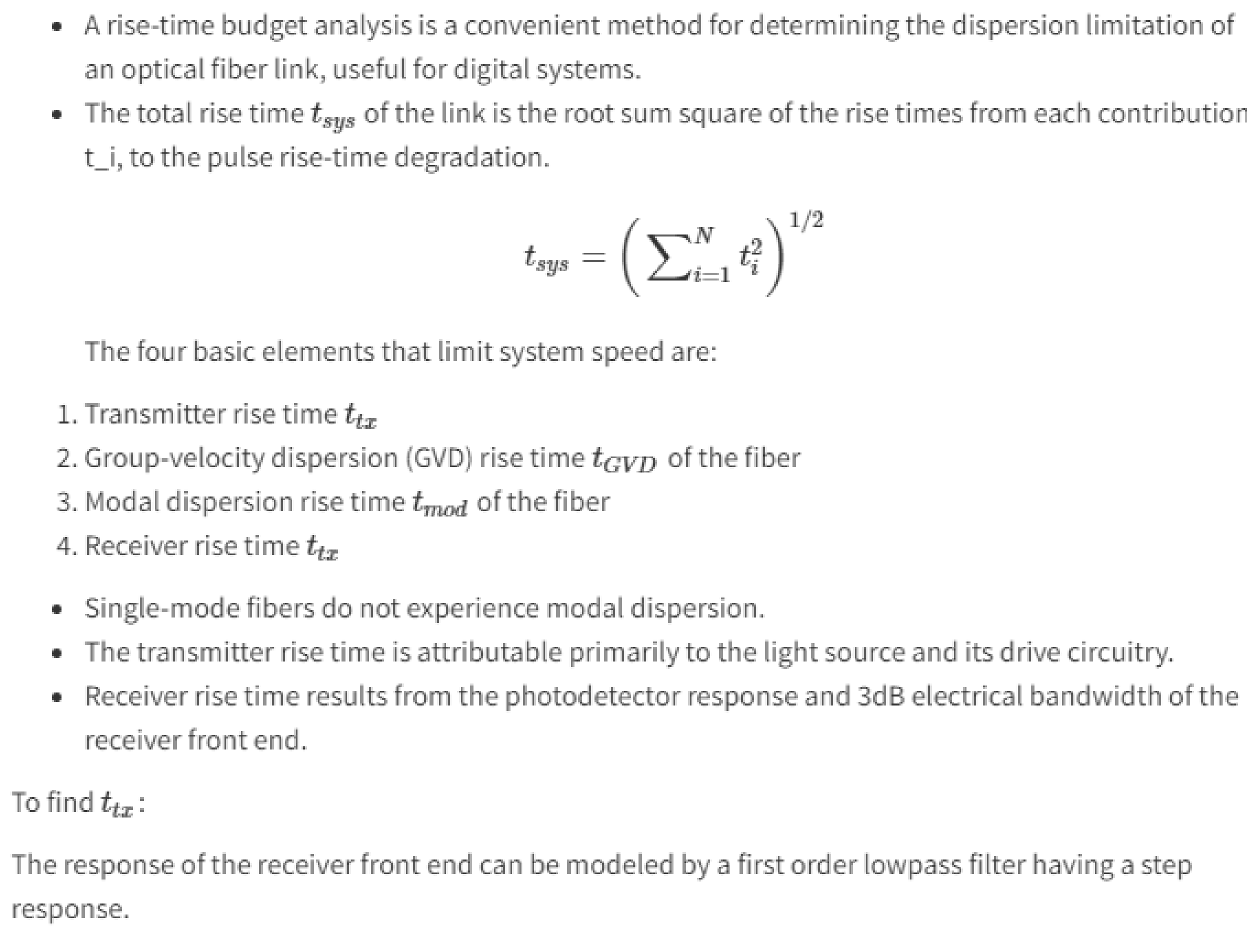
All the losses from source to detector comprises the total loss (PT) in the system. Link power margin considers the losses due to component aging and temperature fluctuations. Usually a link margin of 6-8 dB is considered while estimating link power budget.

Total optical loss = Connector loss + (Splicing loss + Fiber attenuation) + System margin (Pm)

PT = 2lc + αfL + System margin (Pm)

where, L is transmission distance.

Rise Time Budget:-



- A rise-time budget analysis is a convenient method for determining the dispersion limitation of an optical fiber link, useful for digital systems.
- The total rise time t_{sys} of the link is the root sum square of the rise times from each contribution t_i, to the pulse rise-time degradation.

$$t_{sys} = \left(\sum_{i=1}^{N} t_i^2 \right)^{1/2}$$

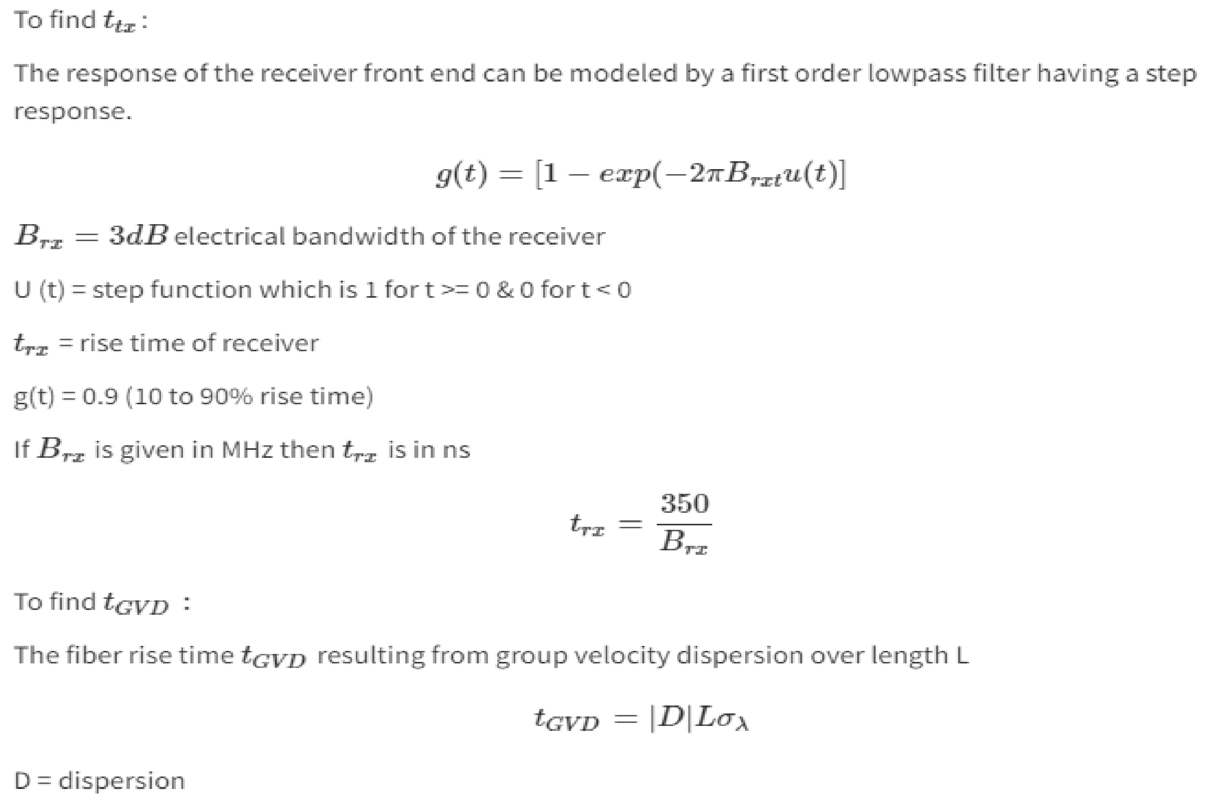
The four basic elements that limit system speed are:

1. Transmitter rise time t_{tx}
2. Group-velocity dispersion (GVD) rise time t_{GVD} of the fiber
3. Modal dispersion rise time t_{mod} of the fiber
4. Receiver rise time t_{tx}

- Single-mode fibers do not experience modal dispersion.
- The transmitter rise time is attributable primarily to the light source and its drive circuitry.
- Receiver rise time results from the photodetector response and 3dB electrical bandwidth of the receiver front end.

To find t_{tx}:

The response of the receiver front end can be modeled by a first order lowpass filter having a step response.



To find t_{tx}:

The response of the receiver front end can be modeled by a first order lowpass filter having a step response.

$$g(t) = [1 - exp(-2\pi B_{rxt} u(t)]$$

$B_{rx} = 3dB$ electrical bandwidth of the receiver

U (t) = step function which is 1 for t >= 0 & 0 for t < 0

t_{rx} = rise time of receiver

g(t) = 0.9 (10 to 90% rise time)

If B_{rx} is given in MHz then t_{rx} is in ns

$$t_{rx} = \frac{350}{B_{rx}}$$

To find t_{GVD} :

The fiber rise time t_{GVD} resulting from group velocity dispersion over length L

$$t_{GVD} = |D| L \sigma_\lambda$$

D = dispersion

σ_λ = Half power band width of source

To find t_{mod} :

Empirical relation for bandwidth B_M of link length L:

$$B_M(L) = \frac{B_0}{Lq}$$

Where 0.5 < q < 1

B_0 = Bandwidth of 1km length of fiber cable

- 3dB bandwidth is defined as modulation frequency f_{3dB} at which received optical power has fallen to 0.5 of zero frequency value.

$$f_{3dB} = B_{3dB} = \frac{0.44}{t_{FWHM}}$$

- Letting t_{FWHM} be the rise time resulting from modal dispersion.

$$t_{mod} = \frac{0.44}{B_M} = \frac{0.44L^q}{B_0}$$

- If t_{mod} is in ns & B_M is in MHz

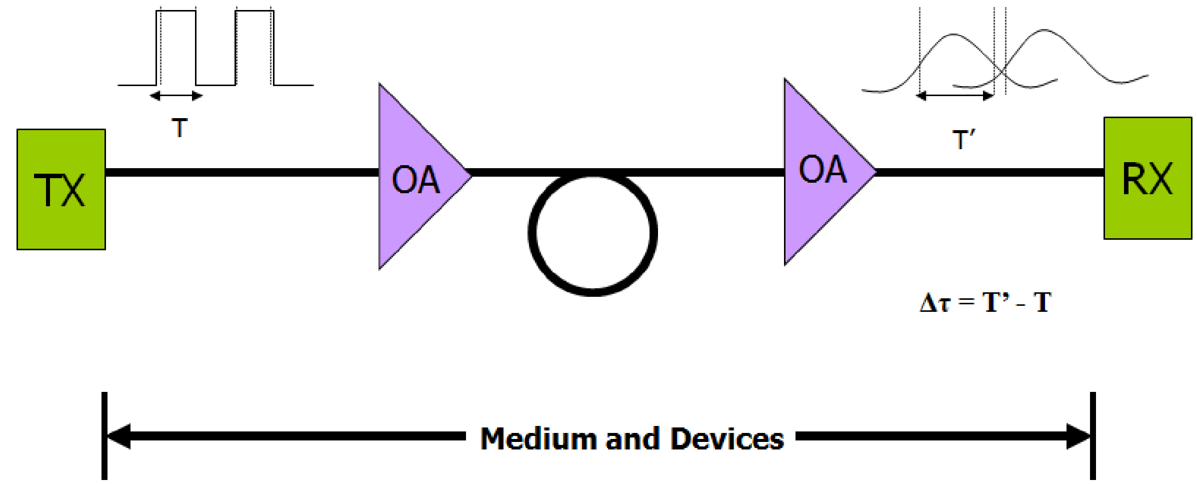
$$t_{mod} = \frac{440}{B_M} = \frac{440L^q}{B_0}$$

- Total rise time of a fiber link is the root - sum - square of rise time of each contributor to the pulse rise time degradation.

$$t_{sys} = \sqrt{t_{tx}^2 + t_{mod}^2 + t_{GVD}^2 + t_{rx}^2}$$
$$t_{sys} = \sqrt{t_{tx}^2 + \left(\frac{440L^q}{B_0}\right)^2 + (DL\sigma_\lambda)^2 + \left(\frac{350}{B_{rx}}\right)^2}$$

All the times are in nanoseconds.

Bandwidth Budget:-



$$\mathrm{BW} = 0.35/\ t\ \mathrm{sys}$$

POWER BUDGET:-

Power budgeting process

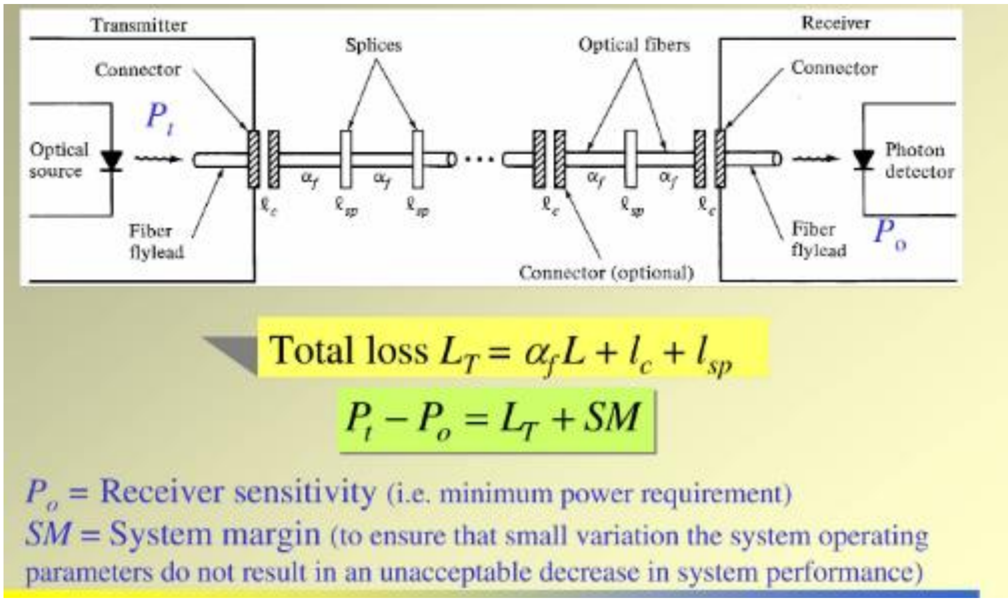
Figure 16.1 shows a hypothetical point-to-point link. Here there are connectors on each end of the link and N splices located periodically along the cable length. The optical power arriving at the photodetector depends on the amount of light coupled into the fiber minus the losses incurred along the path. The link loss budget is derived from the sequential loss contributions of each element in the link. Each of these losses is expressed in decibels as

$$\text{Loss} = 10 \log \frac{P_{\text{out}}}{P_{\text{in}}}$$

where P_{in} and P_{out} are the optical powers entering and exiting, respectively, a fiber, splice, connector, or other link element.

The link loss budget simply considers the total optical power loss P_T that is allowed between the light source and the photodetector and allocates this loss to factors such as cable attenuation, connector and splice losses, losses in other link components, and system margin. Thus, referring to Fig. 16.1, if P_S is the optical power emerging from the end of a fiber flylead attached to the source and if P_R is the minimum receiver sensitivity needed for a specific BER, then

$$\begin{aligned} P_T &= P_S - P_R \\ &= 2 \times \text{connector loss} + \alpha L + N \times \text{splice loss} \\ &\quad + \text{other losses} + \text{system margin} \end{aligned}$$



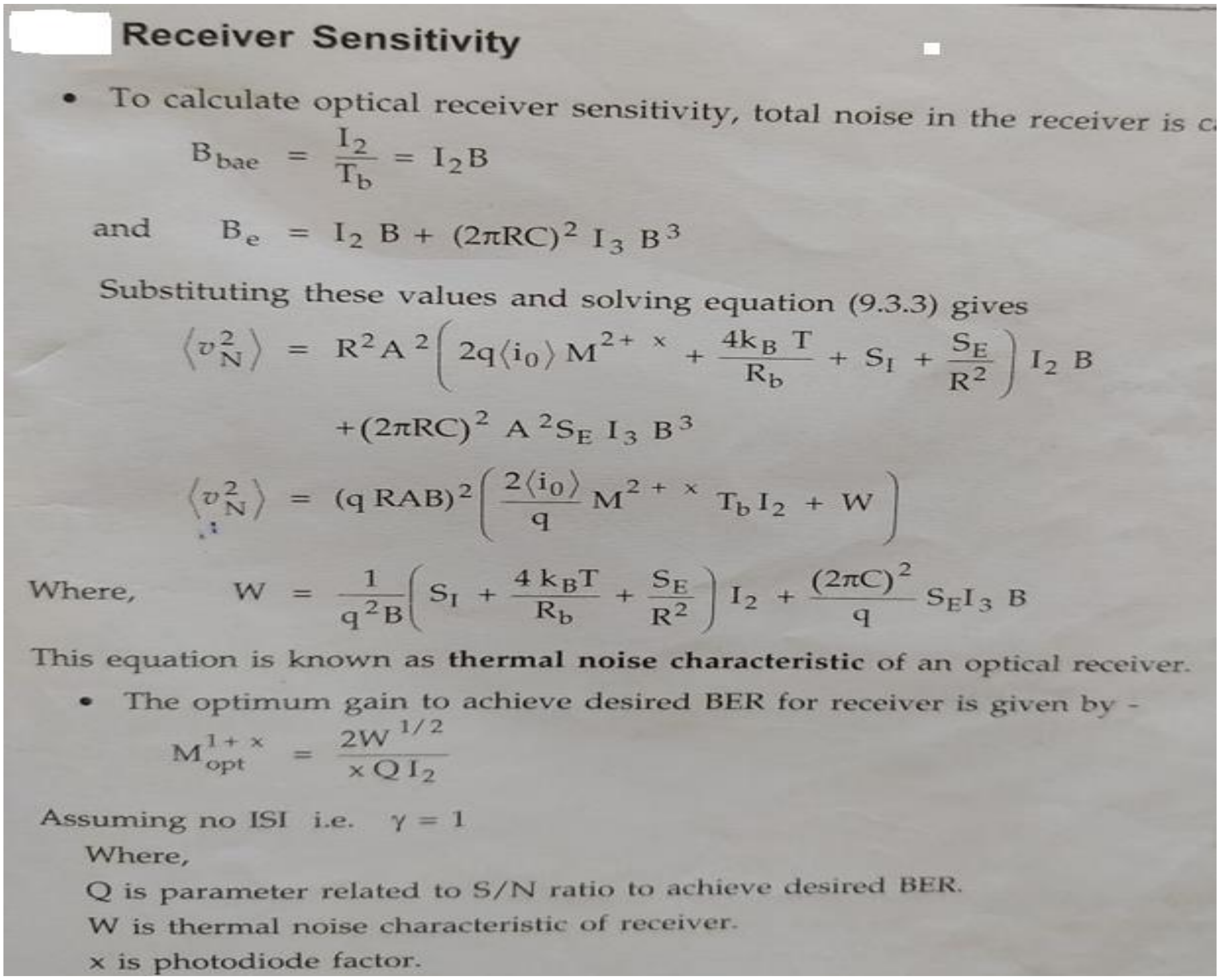
Total loss $L_T = \alpha_f L + l_c + l_{sp}$

$$P_t - P_o = L_T + SM$$

P_o = Receiver sensitivity (i.e. minimum power requirement)

SM = System margin (to ensure that small variation the system operating parameters do not result in an unacceptable decrease in system performance)

RECIEVER SENSITIVITY:-



Receiver Sensitivity

- To calculate optical receiver sensitivity, total noise in the receiver is c

$$B_{bae} = \frac{I_2}{T_b} = I_2 B$$

and $\quad B_e = I_2 B + (2\pi RC)^2 I_3 B^3$

Substituting these values and solving equation (9.3.3) gives

$$\langle v_N^2 \rangle = R^2 A^2 \left(2q \langle i_0 \rangle M^{2+x} + \frac{4k_B T}{R_b} + S_I + \frac{S_E}{R^2} \right) I_2 B$$

$$+ (2\pi RC)^2 A^2 S_E I_3 B^3$$

$$\langle v_N^2 \rangle = (q\, RAB)^2 \left(\frac{2\langle i_0 \rangle}{q} M^{2+x} T_b I_2 + W \right)$$

Where, $\quad W = \frac{1}{q^2 B} \left(S_I + \frac{4k_B T}{R_b} + \frac{S_E}{R^2} \right) I_2 + \frac{(2\pi C)^2}{q} S_E I_3 B$

This equation is known as **thermal noise characteristic** of an optical receiver.

- The optimum gain to achieve desired BER for receiver is given by -

$$M_{opt}^{1+x} = \frac{2W^{1/2}}{x Q I_2}$$

Assuming no ISI i.e. $\gamma = 1$

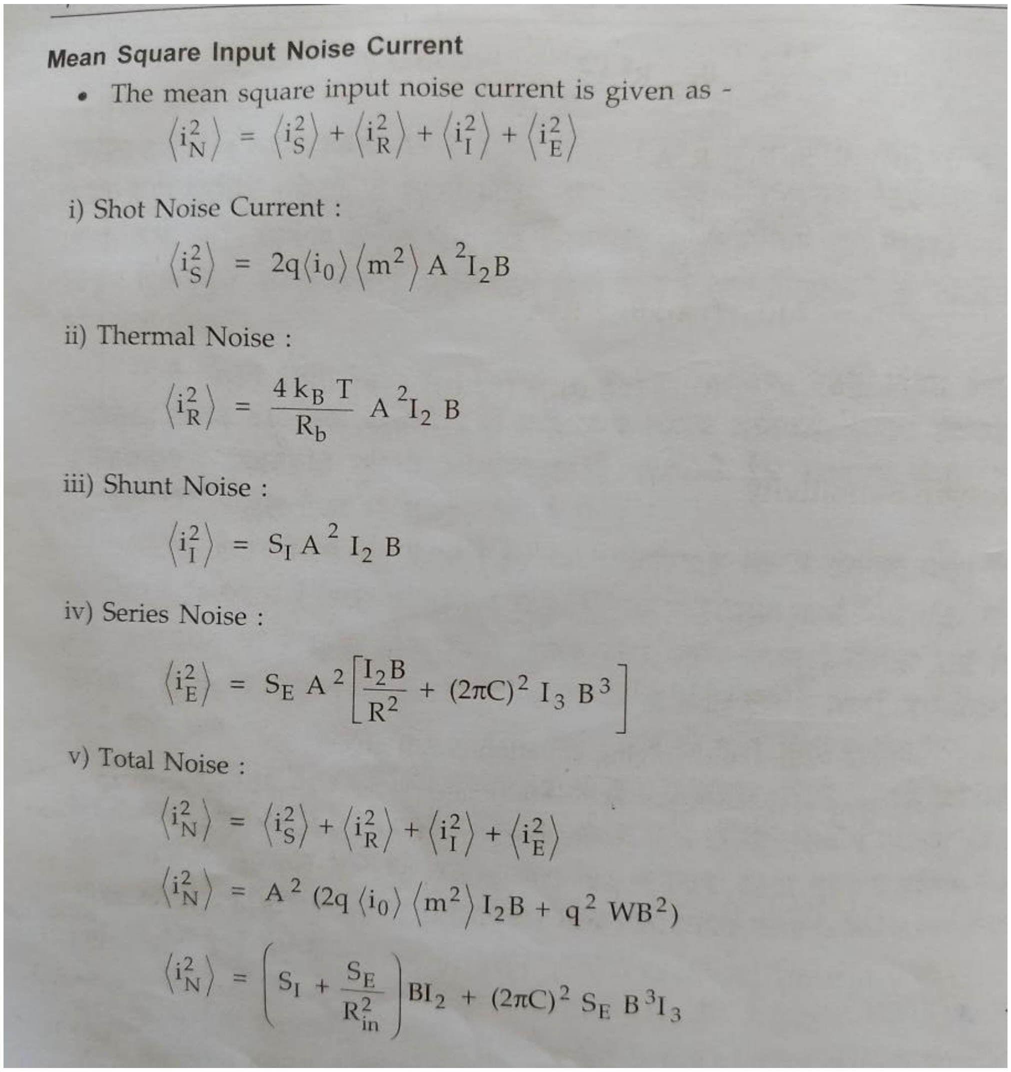
Where,

Q is parameter related to S/N ratio to achieve desired BER.

W is thermal noise characteristic of receiver.

x is photodiode factor.

I_2 is Normalised Bandwidth



Mean Square Input Noise Current

- The mean square input noise current is given as -

$$\langle i_N^2 \rangle = \langle i_S^2 \rangle + \langle i_R^2 \rangle + \langle i_I^2 \rangle + \langle i_E^2 \rangle$$

i) Shot Noise Current :

$$\langle i_S^2 \rangle = 2q\langle i_0 \rangle \langle m^2 \rangle A^2 I_2 B$$

ii) Thermal Noise :

$$\langle i_R^2 \rangle = \frac{4 k_B T}{R_b} A^2 I_2 B$$

iii) Shunt Noise :

$$\langle i_I^2 \rangle = S_I A^2 I_2 B$$

iv) Series Noise :

$$\langle i_E^2 \rangle = S_E A^2 \left[\frac{I_2 B}{R^2} + (2\pi C)^2 I_3 B^3\right]$$

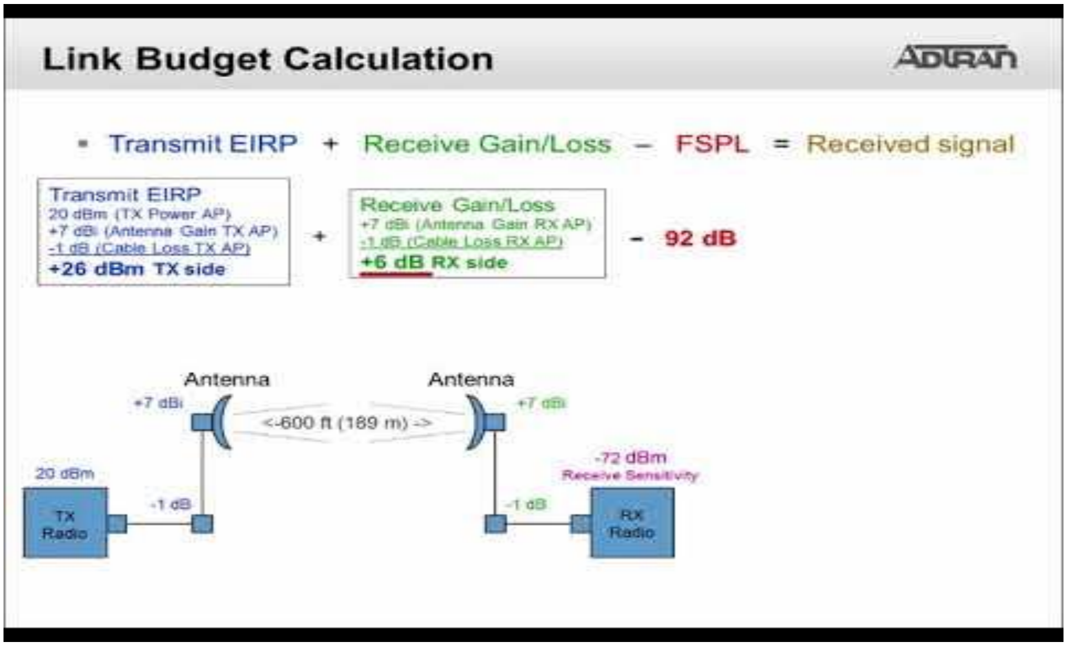
v) Total Noise :

$$\langle i_N^2 \rangle = \langle i_S^2 \rangle + \langle i_R^2 \rangle + \langle i_I^2 \rangle + \langle i_E^2 \rangle$$

$$\langle i_N^2 \rangle = A^2 (2q \langle i_0 \rangle \langle m^2 \rangle I_2 B + q^2 WB^2)$$

$$\langle i_N^2 \rangle = \left(S_I + \frac{S_E}{R_{in}^2} \right) BI_2 + (2\pi C)^2 S_E B^3 I_3$$

LINK BUDGET CALCULATIONS:-



Link Budget Calculation

ADTRAN

- Transmit EIRP + Receive Gain/Loss – FSPL = Received signal

Transmit EIRP
20 dBm (TX Power AP)
+7 dBi (Antenna Gain TX AP)
-1 dB (Cable Loss TX AP)
+26 dBm TX side

\+

Receive Gain/Loss
+7 dBi (Antenna Gain RX AP)
-1 dB (Cable Loss RX AP)
+6 dB RX side

– **92 dB**

OPTICAL MULTIPLEXING AND DEMULTIPLEXING:-

- Transmitting two or more signals simultaneously can be accomplished by setting up one transmitter receiver pair for each channel, but this is an expensive approach.
- A single cable or radio link can handle multiple signals simultaneously using a technique known as multiplexing.
- Multiplexing permits hundreds or even thousands of signals to be combined and transmitted over a single medium.
- Cost savings can be gained by using a single channel to send multiple information signals.

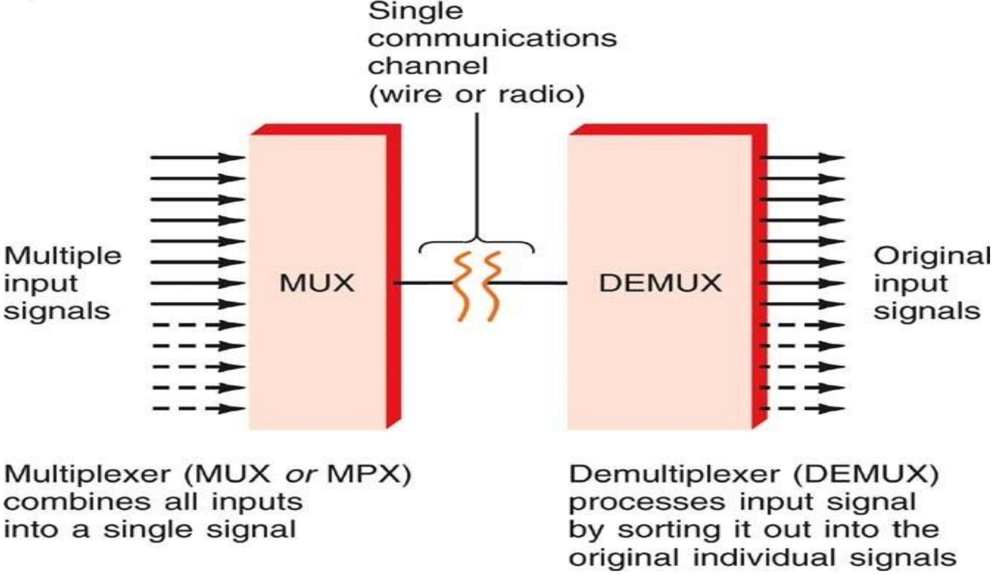


FIG.4.3 CONCEPT OF MULTIPLEXING

Multiplexing is method or technique in which more than one signals are combined into one signal that travels on a medium.

Demultiplexing is the reverse of multiplexing, in which a multiplexed signal is decomposed in individual signals.

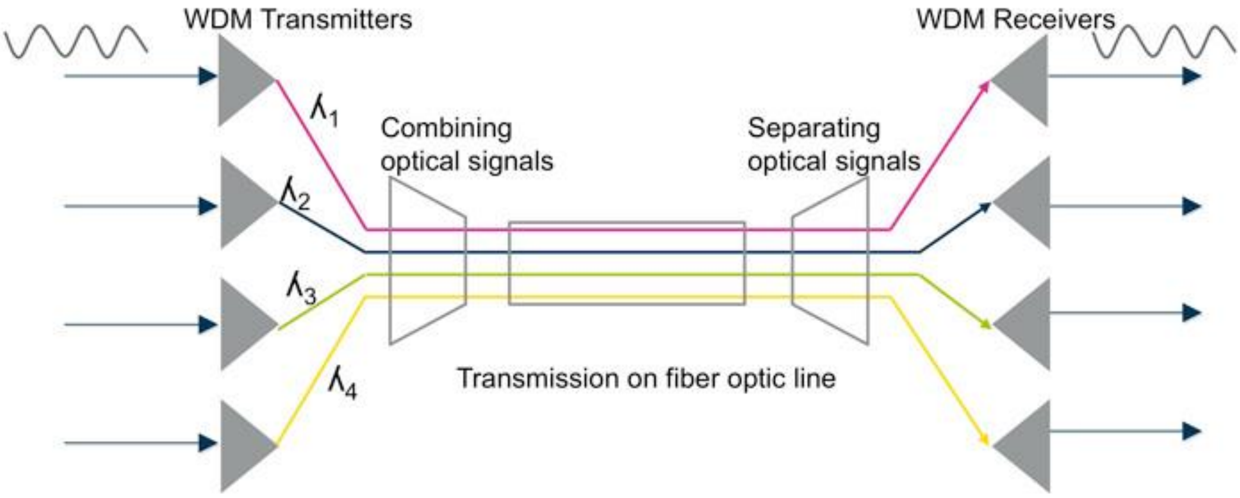
Currently, multiplexing technologies have used many dimensions to increase optical transmission system capacity over a fixed bandwidth. Two major methods are WDM and OTDM.

Wavelength Division Multiplexing

WDM is one of the optical multiplexing techniques that increases bandwidth by multiplexing a variety of optical carrier signals onto a single optical fiber by using different wavelengths. Each signal at WDM wavelengths is independent of any protocol and any speed. The WDM technology allows bidirectional communications simultaneously over a single optical fiber. The foundation of WDM simplifies the network to a single virtual optical fiber network instead of using multiple forms of signals with different fibers and services. In this way, WDM increases the bandwidth and lowers the networking cost by reducing the needed fibers.

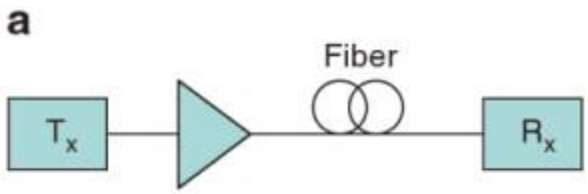
There are two different wavelength patterns of WDM systems, coarse (CWDM) and dense (DWDM). CWDM and DWDM are based on the same concept of using multiple light wavelengths on a single fiber, but differ in the spacing of the wavelengths, numbers of channels, and the ability to amplify the multiplexed signals in the optical space. In a WDM system, different optical signals are combined (multiplexed) together at one end of the optical fiber and separated (demultiplexed) into different channels at the other end.

The optical carrier WDM is often regarded as an analogous technique of frequency division multiplexing, which typically applies to a radio carrier. However, there is no essential difference between them since they communicate the same information.



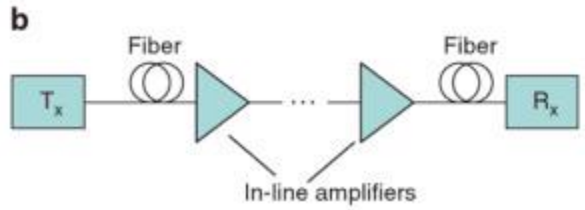
OPTICAL AMPLIFIERS AND ITS APPLICATIONS:-

Optical amplifiers can be used at many points in a communication link for several system applications. Three common applications of optical amplifiers are power boosters (of transmitters), in-line amplifiers, and optical pre-amplifiers.

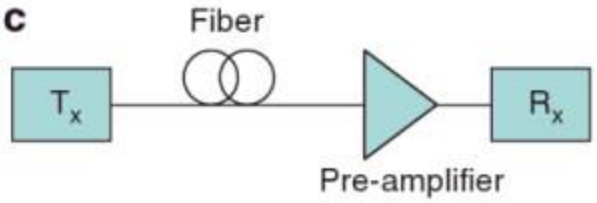


Booster (power) amplifier

The booster (power) amplifiers are placed at the optical transmitter side to enhance the transmitted power level or to compensate for the losses of optical elements between the laser and optical fibers, such as optical coupler, splitters, WDM multiplexers, and external optical modulators. In another word, the booster amplifiers are used to boost the power of the transmitter before launching into the fiber link. The increased transmitter power can be used to go farther in the link. In general, the output power of a laser diode or a tunable laser source is moderate, especially if an external modulator is used. The key feature of the booster is a high saturation output power. Further, the booster should provide bit-pattern effect free amplification of the data signal. In WDM systems it should amplify all signals alike across the spectrum. Booster amplifiers normally are polarization sensitive. This is not an issue for boosters as the input signal polarization is known. Related products in Fiberstore: **Booster Amplifiers**



The in-line amplifiers are placed along the transmission link to compensate for the losses incurred during the propagation of optical signal. They are used at intermediate points in the link to overcome fiber transmission and other distribution losses. An in-line amplifier mainly compensates for fiber losses or splitter losses in an optical transmission system. It takes a small input signal and boosts it for retransmission down the fiber. The most important performance parameters are saturation output power and noise figure because the incoming signals are weak. Controlling the small-signal performance and noise will provide better system results. Noise added by amplifiers in series will limit the system length. The polarization dependence of the gain should be as small as possible due to the random state of polarization within a network. Also, the in-line amplifier needs to cope with several wavelength channels simultaneously. Further, in-line amplifier should process the data signal “transparently” which means that all kinds of modulation formats at ant data rate should be amplified without significant degradation. In addition, there is an increasing interest in low wall-plug power consumption since in-line amplifiers might be placed outside of network central offices. Related products in Fiberstore: **In-line Amplifiers**



The optical pre-amplifiers are placed just before the receiver to increase the signal level before the photodetection takes place in an ultra-long-haul system and thus provide improvement in the receiver sensitivity. In this case, the receiver sensitivity depends on the amplifier gain, noise figure and optical bandwidth which are the most important parameters of a pre-amplifier. Hence, a pre-amplifier should have a low noise figure and a high gain (not high power) for optimum receiver performance. Typical commercial pre-amplified receivers (i.e. the pre-amplifier) operate with an input signal level of the order of -30 dBm at 10 Gbps.

UNIT-V

OPTICAL NETWORKS

SONET/SDH

Introduction

- SONET is the TDM optical network standard for North America
- SONET is called Synchronous Digital Hierarchy (SDH) in the rest of the world
- SONET is the basic physical layer standard
- Other data types such as ATM and IP can be transmitted over SONET
- OC-1 consists of 810 bytes over 125 us; OC-n consists of 810n bytes over 125 us
- Linear multiplexing and de-multiplexing is possible with Add-Drop-Multiplexers
- The SONET/SDH standards enable the interconnection of fiber optic transmission equipment from various vendors through multiple-owner trunk networks.
- The basic transmission bit rate of the basic SONET signal is
- In SDH the basic rate is 155.52 Mb/s.

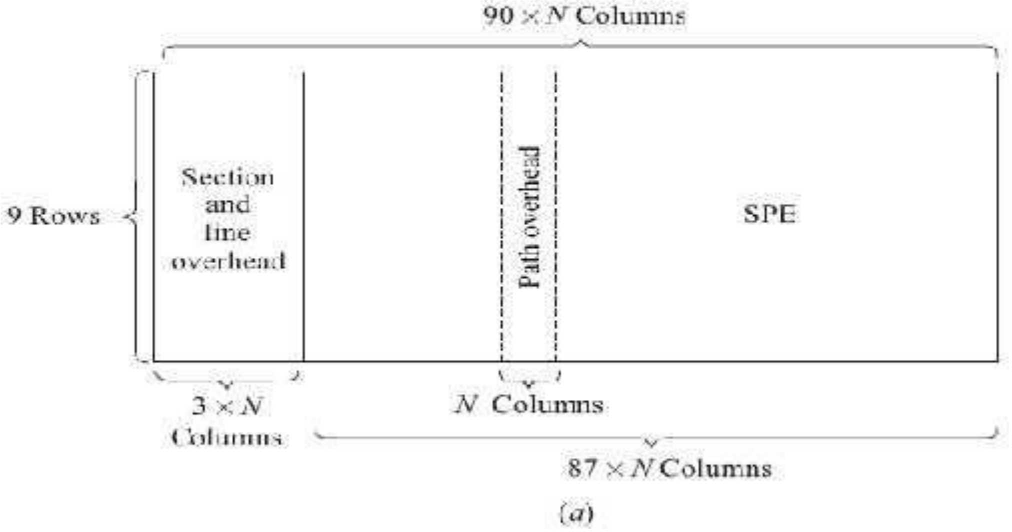


Figure Basic formats of an STS-N SONET frame

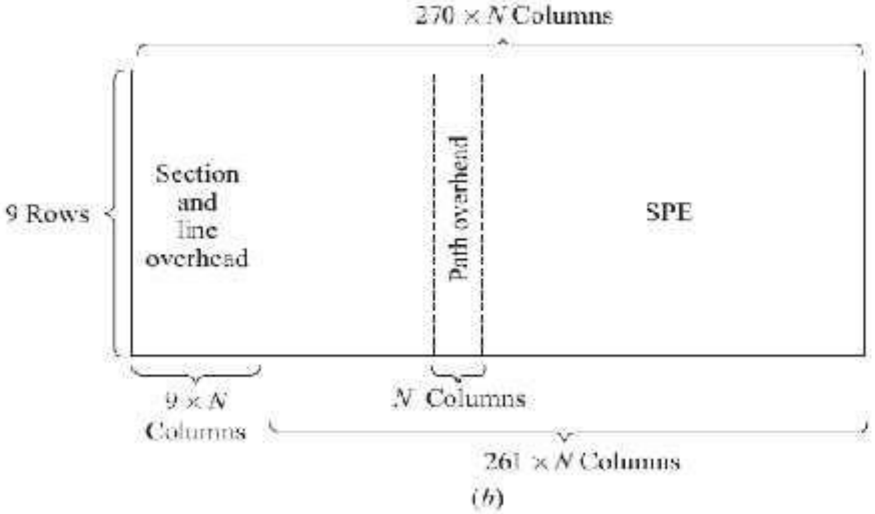


Figure Basic formats of an STM-N SDH frame

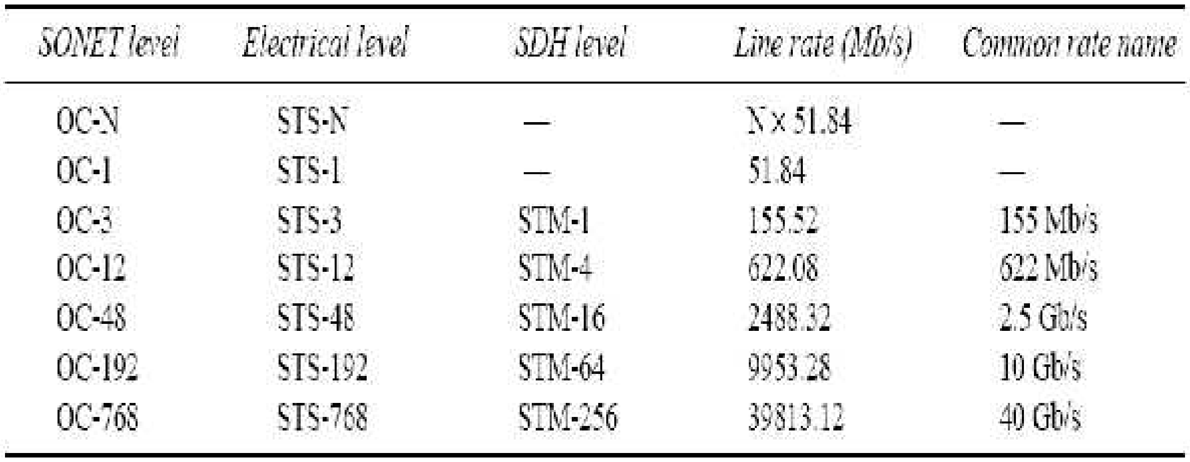
Common values of OC-N and STM-N:

- OC stands for optical carrier. It has become common to refer to SONET links as OC- N links.
- The basic SDH rate is 155.52 Mb/s and is called the synchronous transport module-level 1 (STM 1).

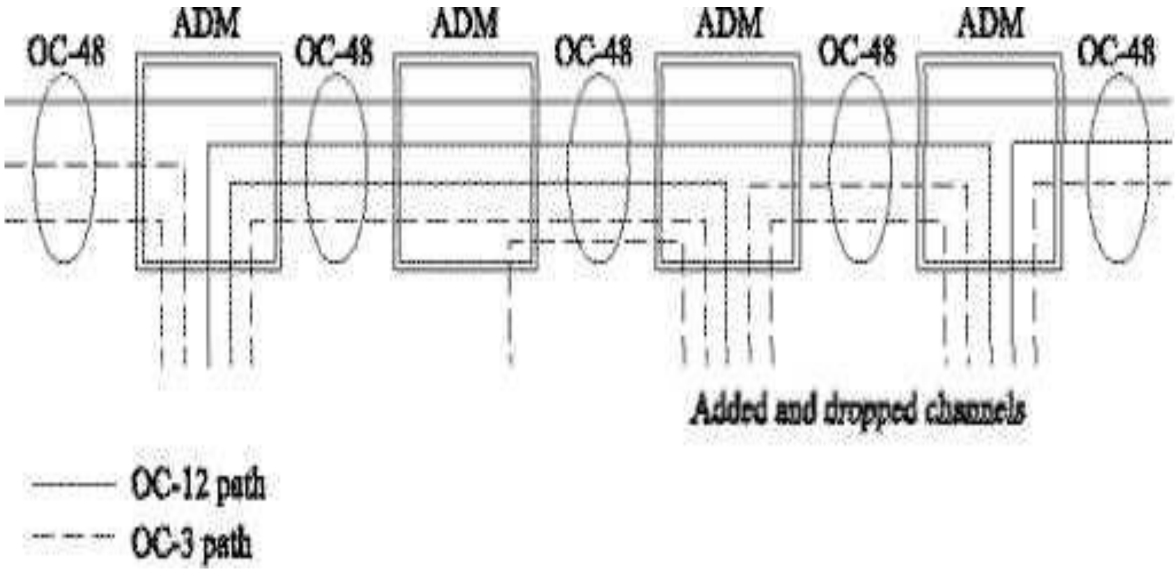
SONET Add Drop Multiplexers:

SONET ADM is a fully synchronous, byte oriented device, that can be used add/drop OC sub- channels within an OC-*N* signal

Ex: OC-3 and OC-12 signals can be individually added/ dropped from an OC-48 carrier

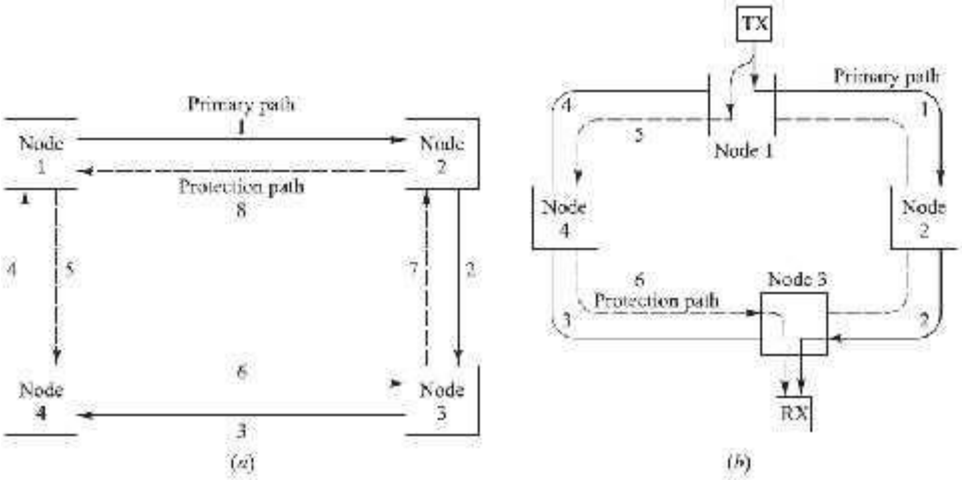


SONET level	*Electrical level*	*SDH level*	*Line rate (Mb/s)*	*Common rate name*
OC-N	STS-N	—	N × 51.84	—
OC-1	STS-1	—	51.84	—
OC-3	STS-3	STM-1	155.52	155 Mb/s
OC-12	STS-12	STM-4	622.08	622 Mb/s
OC-48	STS-48	STM-16	2488.32	2.5 Gb/s
OC-192	STS-192	STM-64	9953.28	10 Gb/s
OC-768	STS-768	STM-256	39813.12	40 Gb/s



SONET/SDH Rings:

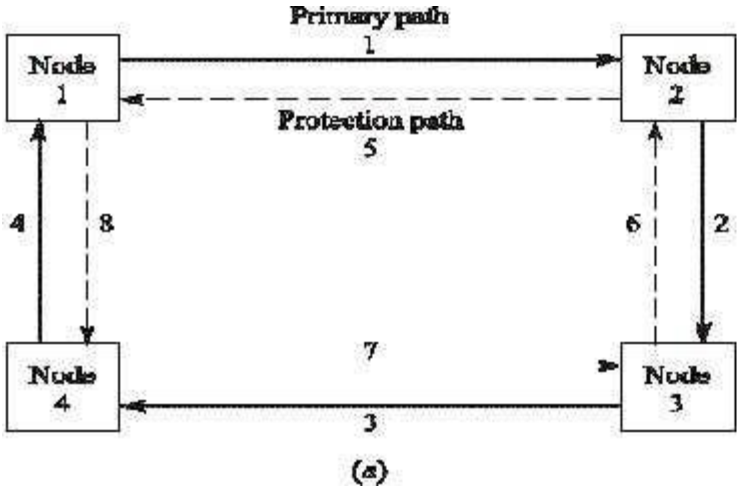
- SONET and SDH can be configured as either a ring or mesh architecture
- SONET/SDH rings are self-healing rings because the traffic flowing along a certain path can be switched automatically to an alternate or standby path following failure or degradation of the link segment
- Two popular SONET and SDH networks:
  - 2-fiber, unidirectional, path-switched ring (2-fiber UPSR)
  - 2-fiber or 4-fiber, bidirectional, line-switched ring (2-fiber or 4-fiber BLSR)



(a) (b)

Figure Generic 2-fiber UPSR with a counter-rotating protection path

2-Fiber UPSR Basics:



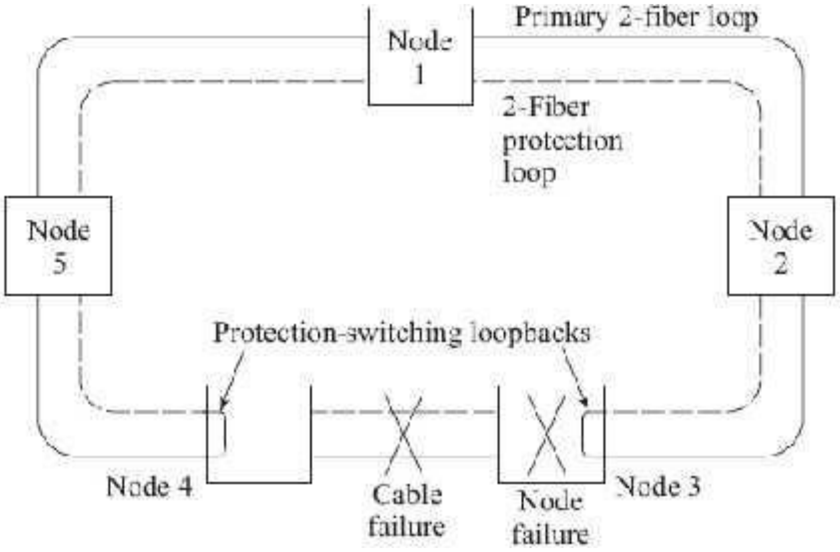
Ex: Total capacity OC-12 may be divided to four OC-3 streams, the OC-3 is called a path here

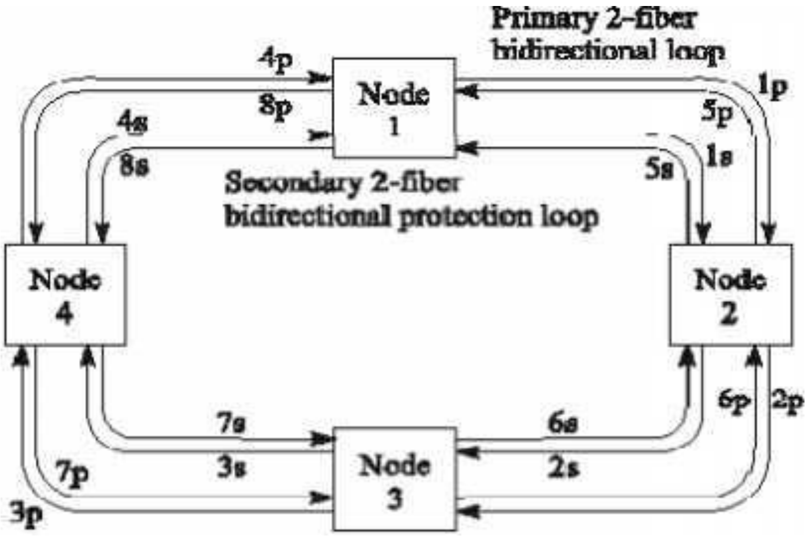
2-Fiber UPSR Protection:

- ❖ Rx compares the signals received via the primary and protection paths and picks the best one
- ❖ Constant protection and automatic switching

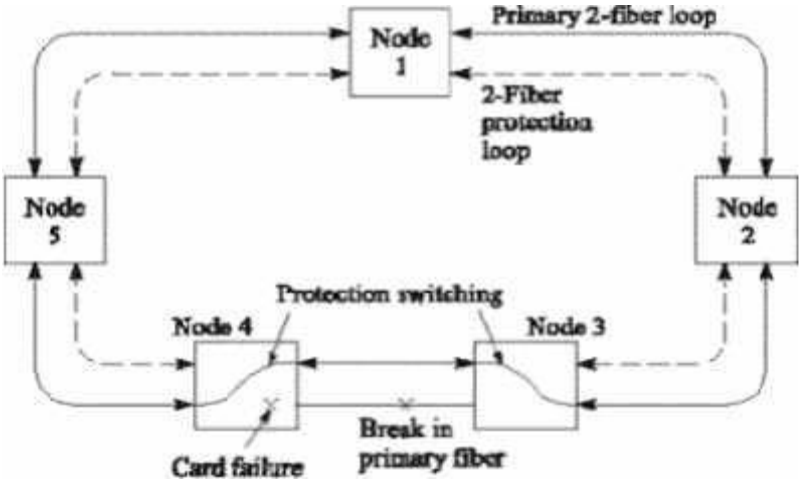
4-Fiber BLSR Basics:

Node 1→ 3; 1p, 2p   Node3→ 1;3p, 4p



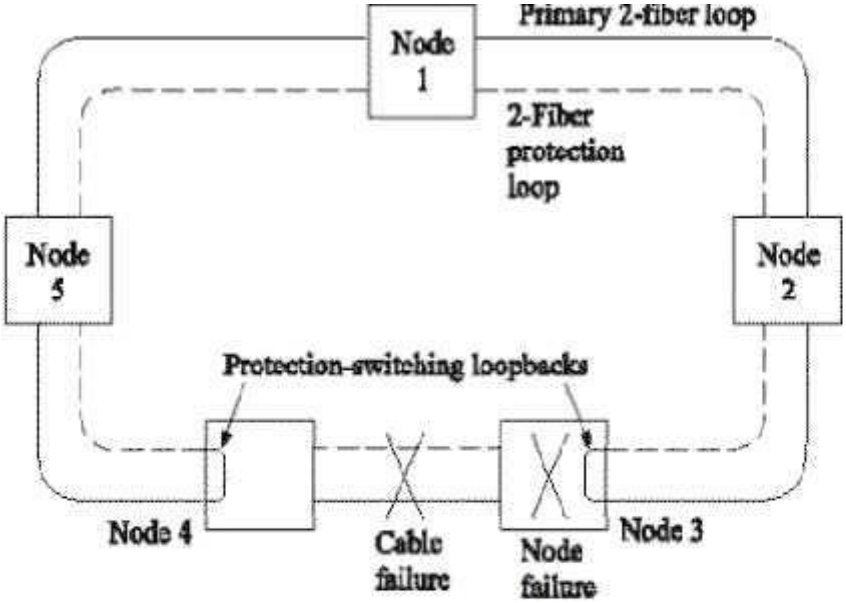


BLSR Fiber-Fault Reconfiguration:



In case of failure, the secondary fibers between only the affected nodes (3 & 4) are used, the other links remain unaffected

BLSR Node-Fault Reconfiguration



If both primary and secondary are cut, still the connection is not lost, but both the primary and secondary fibers of the entire ring is occupied

BLSR Recovery from Failure Modes:

- If a primary-ring device fails in either node 3 or 4, the affected nodes detect a loss-of-signal condition and switch both primary fibers connecting these nodes to the secondary protection pair

- If an entire node fails or both the primary and protection fibers in a given span are severed, the adjacent nodes switch the primary-path connections to the protection fibers, in order to loop traffic back to the previous node.

Broadcast and Select WDM Networks

Optical signals of different wavelength can propagate without interfering with each other. The scheme combining a number of wavelengths over a single fiber is wavelength division multiplexing.

Two categories of broadcast and select WDM networks

1. Single hop networks

2. Multihop networks

Broadcast and select single hop networks

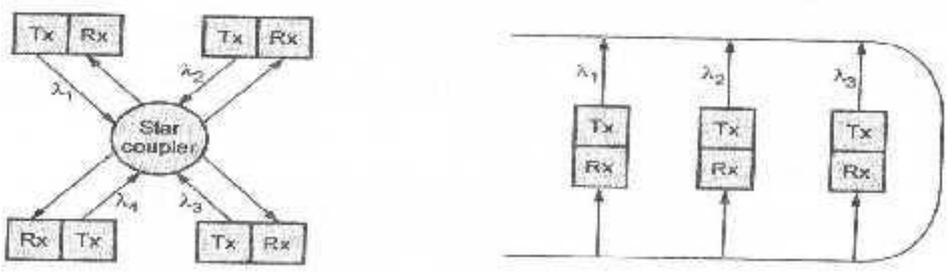


Fig: star configuration and bus configuration

In single hop network, data transmitted reaches its destination without being converted toelectrical energy at any intermediate point

Two physical configurations: star and bus

Each transmitter sends its information at different wavelengths. All transmissions from various nodes are combined in a passive star coupler or coupled onto a bus. The result is sent to all receivers. A coupler is a device which is used to combine and split signals in an optical network. Each receiver sees all wavelengths and uses a tunable filter to select the particular wavelength.

Passive star topology is attractive

- No tapping or insertion loss

- Logarithmic splitting loss in the coupler Advantages of single hop networks

- Simple network architecture

- Protocol transparent

Disadvantages

- It needs rapidly tunable lasers

Broadcast and select multihop networks

Intermediate electro optical conversion may take place. Each node has fixed tuned optical transmitters and receivers. Each node transmits signals on its wavelengths and presented to WDM mux.

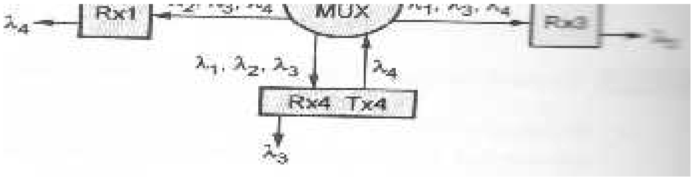


Figure multihop broad cast and select networks

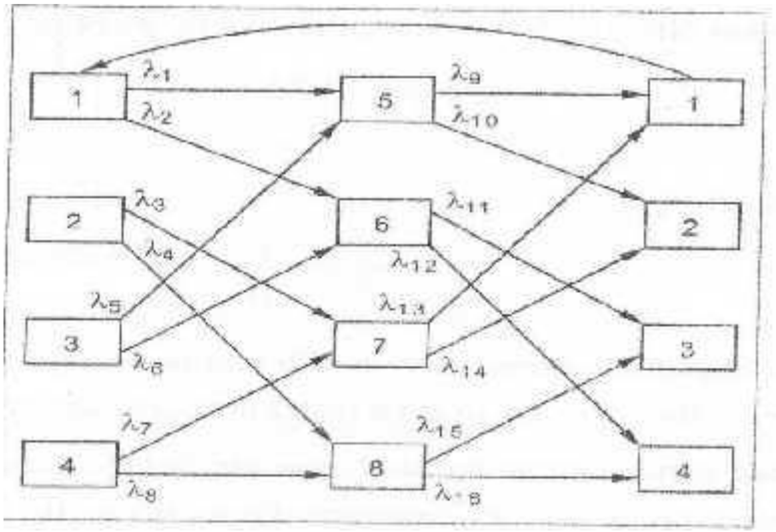


Figure logical interconnection pattern and wavelength assignment of a(p,) = (2,2) shuffle net

A WDM mux is a passive device that does wavelength division multiplexing and transmits a multiplexed signal further along the fiber

Shuffle net Multi hop network

One of the topologies for multihop networks is shuffle net. A cylindrical arrangement of 'k' columns, each having 'P_k' nodes where P is the number of fixed transceiver per node.

Total number of nodes, $N = k P_k$ with k = 1,2,3… and P =1,2,3..

Each node requires P wavelengths to transmit information, the total number of wavelengths $N_\lambda = PN = k P_k+1$

Maximum no. of hops = Hmax = 2^{k-1}. Consider the connections between node 1 and 5 and between nodes 1 and 7. First case hop number is one. Second case, three hops are needed. Per user throughput 'S' = C/N, where C= total network capacity

Advantages of multihop networks

1. No packet collision within the network

2. Rapidly tunable lasers are not required

Disadvantages

There is a throughput per delay of 1/H for H hops between nodes.

Wavelength Routed Networks

Three network nodes are interconnected using two wavelength channels where the solid line connecting the nodes represents the available wavelength channel and the dashed line identifies that the wavelength channel is in use.

If the network node 1 is required to connect with node 3 then as indicated in figure. There is no single wavelength channel available to establish a light path between them. When a light path cannot be established on a link using a single wavelength channel it is referred to as a wavelength continuity constraint.

To reduce this wavelength continuity constraint is to switch the wavelength channel at node 2 by converting the incoming wavelength $\lambda2$ to $\lambda1$ (which is available between nodes 2 and 3) to enable a link between node 2 and 3 to be established. The newly set up path uses two wavelengthstages (i.e. two hops) to interconnect nodes 1 and 3. Such networks which employ wavelength conversion devices (or switches) are known as wavelength convertible networks. Three different WDM network architectures employing the wavelength conversion function are Full wavelength conversion, where each network link utilizes a dedicated wavelength converter, is depicted in Figure. All the wavelength channels at the output port of the optical switch will be converted into their compliant wavelength channel by the appropriate wavelength converter (WC).

It is more cost effective to implement networks with fewer and hence shared wavelength converters. The arrangement of wavelength converters organized in a WCB is illustrated in the inset to Figure. This figure depicts a WCB servicing the optical fiber links where only the required wavelength channels are switched through the WCB. By contrast two optical switches are required to construct the shared per node wavelength convertible network architecture indicated in Figure. Optical switch 2 switches the converted wavelength channels to their designated nodes. In dense WDM networks a light path is established by reserving a particular wavelength on the physical links between the source and destination edge nodes.

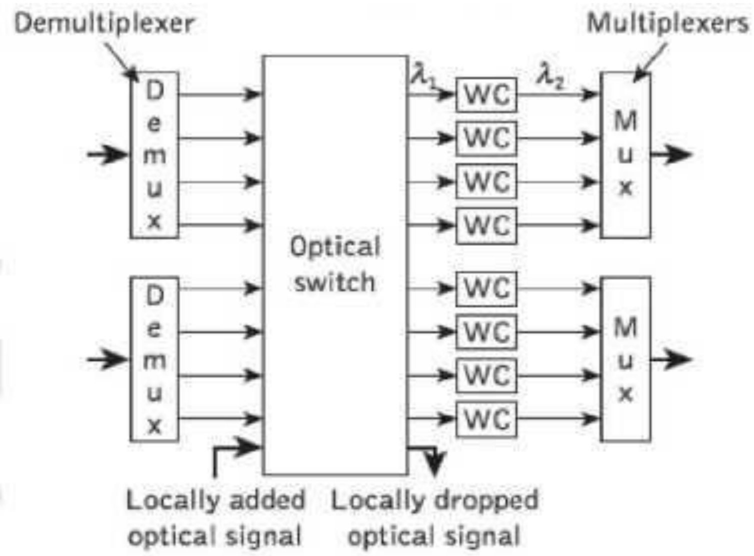


Figure Wavelength convertible routing network architectures: full or rededicated wavelength converters;

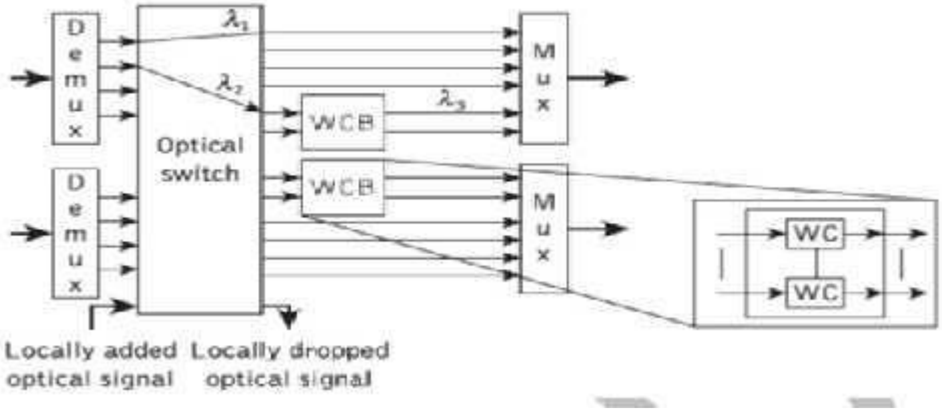


Figure Wavelength convertible routing network architectures: shared per link

It is a two-stage search and-select process related to both routing (i.e. searching/selecting a suitable path) and wavelength assignment (i.e. searching/selecting or allocating an available wavelength for the connection). The overall process is often referred to as the routing and wavelength assignment (RWA) problem. The implementation of RWA can be static or dynamic depending upon the traffic patterns in the network. Static RWA techniques are employed to provide a set of semi permanent connections, which remain active for a relatively longer time.

Dynamic RWA deals with establishing the light path in frequently varying traffic patterns. The traffic patterns are not known and therefore the connection requests are initiated in a random fashion, depending on the network state at the time of a request each time a request is made, an algorithm must be executed in real time to determine whether it is feasible to accommodate the request and, if so, to perform RWA.

A five-node network with fixed connections where node 1 requested to establish a link with node 5 is illustrated in Figure. Although there is no direct physical connection or path available, there are four possibilities to establish the link between nodes 1 and 5, depending on the available or assigned wavelengths between each of the network nodes. These are: via node 2 using a single hop; nodes 4 and 2 comprising two hops; nodes 2 and 3 with two hops; and the longest possible route stretching over three hops via nodes 4, 2 and 3. Considering these four routes, the single hop remains the shortest path between nodes 1 and 5.

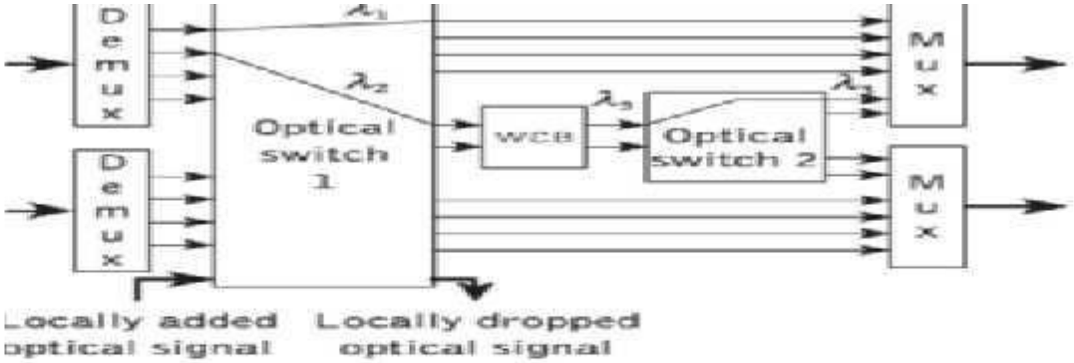


Figure wavelength routing and selection of a path

Non linear effects on Network performance

There are two categories of nonlinear effects.

The first arises due to the interaction of light waves with phonon (molecular vibrations) in the silica medium Rayleigh scattering. The two main effects in this category are stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). The second set of nonlinear effects arises due to the dependence of the refractive index on the intensity of the applied electric field, which in turn is proportional to the square of the field amplitude. The most important nonlinear effects in this category are self-phase modulation (SPM) and four-wave mixing (FWM). Modeling the nonlinear processes can be quite complicated, since they depend on the transmission length, the cross-sectional area of the fiber, and the optical power level in the fiber.

Stimulated Raman scattering

Stimulated Raman scattering is an interaction between light waves and the vibrational modes of silica molecules. If a photon with energy hv1 is incident on a molecule having a vibrational frequency vm, the molecule can absorb some energy from the photon.

In this interaction the photon is scattered, thereby attaining a lower frequency v2 and a corresponding lower energy hv2. The modified photon is called a Stokes photon. Because the optical signal wave that is injected into a fiber is the source of the interacting photons, it is often called the pump wave , since it supplies power for the newly generated wave.

This process generates scattered light at a wavelength longer than that of the incident light. If another signal is present at this longer wavelength, the SRS light will amplify it and the pump wavelength signal will decrease in power

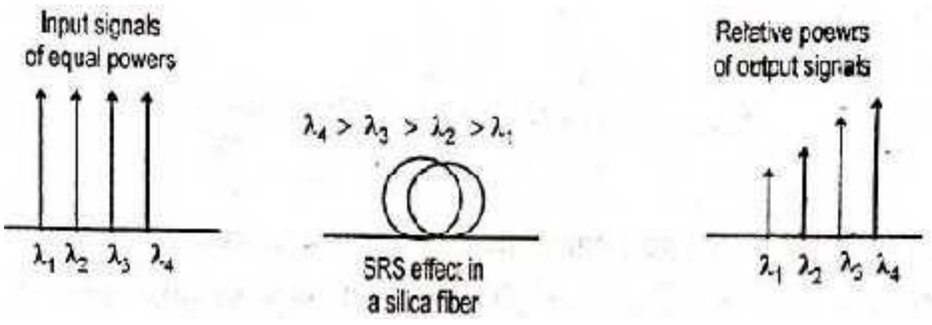


Figure SRS generates scattered light at a longer wavelength, thereby decreasing the power in the pump wavelength signal.

Stimulated Brillouin scattering

Stimulated Brillouin scattering arises when light waves scatter from acoustic waves. The resultant scattered wave propagates principally in the backward direction in single-mode fibers. This backscattered light experiences gain from the forward-propagating signals, which leads to depletion of the signal power. The frequency of the scattered light experiences a Doppler shift

given by $V_B = 2nV_s / \lambda$

where n is the index of refraction and Vs is the velocity of sound in the material.

The effects of SBS accumulate individually for each channel, and consequently they occur at the same power level in each channel as occurs in a single-channel system.

Self-Phase Modulation (SPM)

SPM arises because the refractive index of the fiber has an intensity- dependent component. This nonlinear refractive index causes an induced phase shift that is proportional to the intensity of the pulse. Thus different parts of the pulse undergo a different phase shift which gives rise to chirping of the pulses. Pulse chirping in turn enhances the pulse-broadening effects of chromatic dispersion. This chirping effect is proportional to the transmitted signal power so that SPM effects are more pronounced in systems using high transmitted powers.

In WDM systems, the refractive index nonlinearity gives rise to cross-phase modulation (XPM), which converts power fluctuations in a particular wavelength channel to phase fluctuations in other co propagating channels. This can be mitigated greatly in WDM systems operating over standard non- dispersion shifted single-mode fiber, but can be a significant problem in WDM links operating at 10 Gbps and higher over dispersion-shifted fiber.

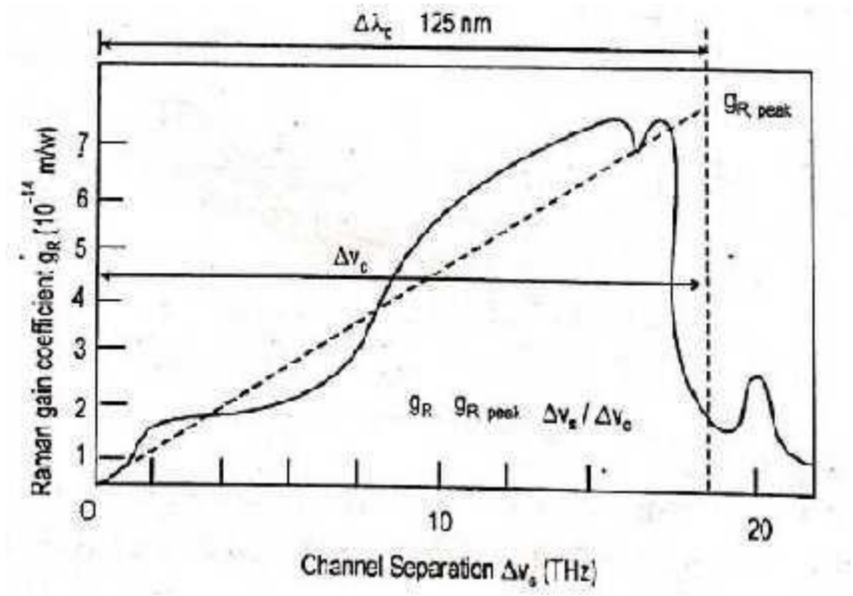


Figure Wavelength Channel separation

Four-wave mixing

Four-wave mixing is a third-order nonlinearity in silica fibers that is analogous to inter modulation distortion in electrical systems. When wavelength channels are located near the zero-dispersion point, three optical frequencies (ν_i, ν_j, ν_k) will mix to produce a fourth inter modulation product νijk given by

$V_{ij}k = V_i + V_j - V_K$ with i,j # k

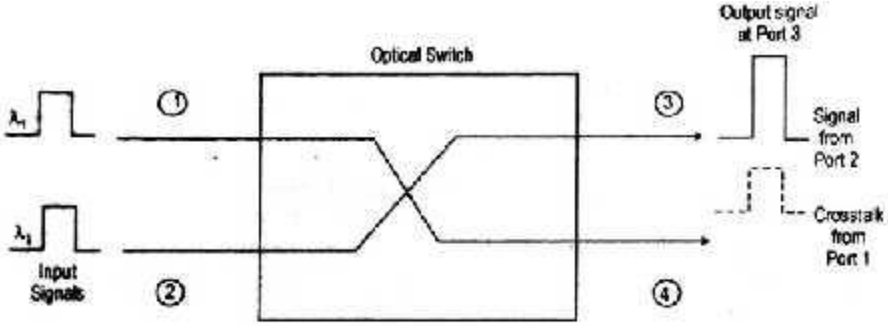


Figure Origin of interchannel crosstalk

Figure shows a simple example for two waves at frequencies ν_1 and ν_2. As these waves co propagate along a fiber, they mix and generate sidebands at

$2V_1 – V_2$ and $2V_2 – v_1$

When this new frequency falls in the transmission window of the original frequencies, it can cause severe crosstalk

LINK POWER BUDGET:

For optimizing link power budget an optical power loss model is to be studied as shown in Figure. Let

- l_c denotes the losses occur at connector.
- L_{sp} denotes the losses occur at splices.
- α_f denotes the losses occur in fiber.

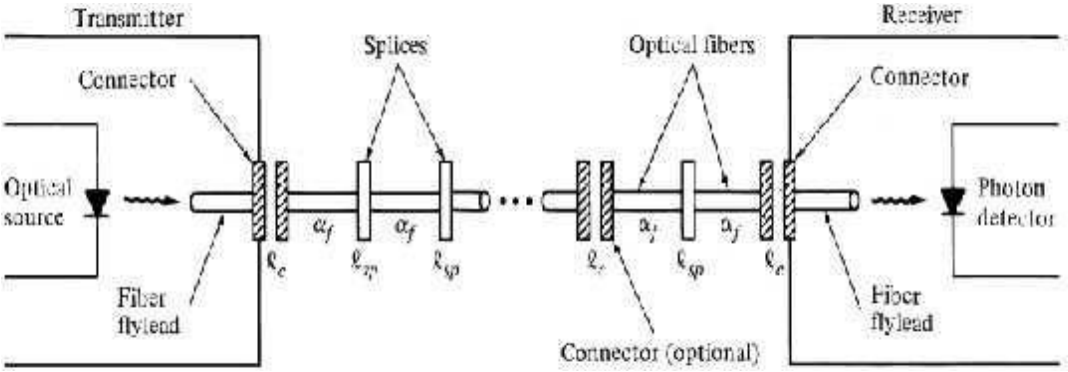


Figure Link power budget

All the losses from source to detector comprises the total loss (P_T) in the system. Link power margin considers the losses due to component aging and temperature fluctuations.

Usually a link margin of 6-8 dB is considered while estimating link power budget. Total optical loss = Connector loss + (Splicing loss + Fiber attenuation) + System margin (P_m)

$$P_T = 2l_c + \alpha_{fL} + \text{System margin } (P_m)$$

Where, L is transmission distance.

Rise Time Budget

Rise time gives important information for initial system design. Rise-time budget analysis determines the dispersion limitation of an optical fiber link. Total rise time of a fiber link is the root-sum-square of rise time of each contributor to the pulse rise time degradation.

$$t_{sys} = \sqrt{t_{r1}^2 + t_{r2}^2 + t_{r3}^2 + \cdots}$$

$$\boxed{t_{sys} = \left(\sum_{i=1}^{N} t_{ri}^2\right)^{1/2}}$$

The link components must be switched fast enough and the fiber dispersion must be low enough to meet the bandwidth requirements of the application adequate bandwidth for a system can be assured by developing a rise time budget. As the light sources and detectors has a finite response time to inputs. The device does not turn-on or turn-off instantaneously. Rise time and fall time determines the overall response time and hence the resulting bandwidth.

Connectors, couplers and splices do not affect system speed, they need not be accounted in rise time budget but they appear in the link power budget. Four basic elements that contributes to the rise-time are, Transmitter rise-time (ttx)

Group Velocity Dispersion (GVD) rise time (t_{GVD}) Modal dispersion rise time of fiber (t_{mod})

Receiver rise time (trx) Where,

Rise time due to modal dispersion is given as

$$\boxed{t_{mod} = \frac{440}{B_M} = \frac{440\,Lq}{B_0}}$$

Where,

B_M is bandwidth (MHz) L is length of fiber (km)

q Is a parameter ranging between 0.5 and 1.

$$\boxed{t_{sys} = \left[t_{tx}^2 + t_{mod}^2 + t_{GVD}^2 + t_{rx}^2\right]^{1/2}}$$

B_0 is bandwidth of 1 km length fiber

Rise time due to group velocity dispersion is

$$t_{GVD} = D^2 \sigma_\lambda^2 L^2$$

Where, D is dispersion [ns/(nm.km)] Σλ is half-power spectral width of source L is length of fiber

Receiver front end rise-time in nanoseconds is

$$\boxed{t_{rx} = \frac{350}{B_{rx}}}$$

B_{rx} is 3 dB – bW of receiver (MHz).

Equation can be written as

$$t_{sys} = \left[t_{tx}^2 + t_{mod}^2 + t_{GVD}^2 + t_{rx}^2\right]^{1/2}$$

$$\boxed{t_{sys} = \left[t_{tx}^2 + \left(\frac{440\,Lq}{\;}\right)^2 + D^2 \sigma_\lambda^2 L^2 + \left(\frac{350}{\;}\right)\right]^{1/2}}$$

WDM

WDM (Wavelength-division Multiplexing) is the technology of combing a number of wavelengths onto the same fiber simultaneously. A powerful aspect of WDM is that each optical channel can carry any transmission format. WDW increases the capacity of a fiber network dramatically. Thus it is recognized as the Layer 1 transport technology in all tiers of the network. The purpose of this article is to give a brief overview of WDM technology and its applications.

NEED OF WDM

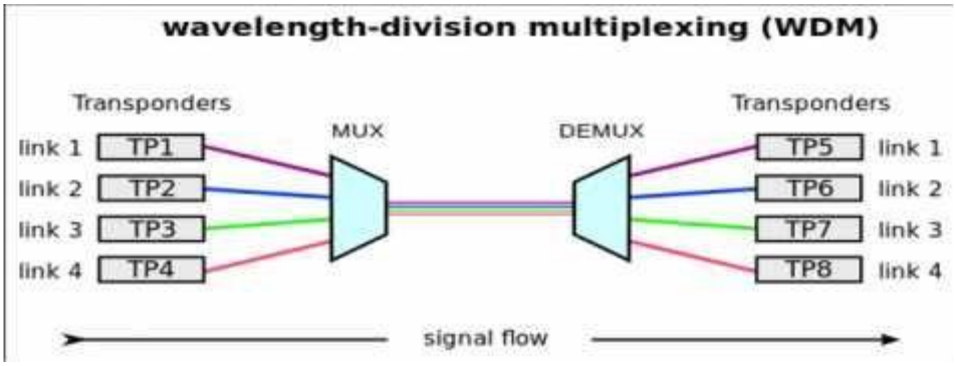
Due to the rapid growth in telecommunication links, high capacity and faster data transmission rates over farther distances are required. To meet these demands, network managers are relying more and more on fiber optics. Typically, there are three methods for expanding capacity: installing more cables, increasing system bit rate to multiplex more signals and wavelength division multiplexing. The first method, installing more cables, will be preferred in many cases, especially in metropolitan areas, since fiber has become incredibly inexpensive and installation methods more efficient. But when conduit space is not available or major construction is necessary, this may not be the most cost-effective.

Another way for capacity expansion is to increase system bit rate to multiplex more signals. But increasing system bit rate may not prove cost effective either. Since many systems are already running at SONET OC-48 rates (2.5 GB/s) and upgrading to OC-192 (10 GB/s) is expensive, requires changing out all the electronics in a network, and adds 4 times the capacity, may not be necessary. Thirdly, the WDM has been proved to be the more cost-effective technology. It does not only support current electronics and fibers but also can share fibers by transmitting channels at different wavelengths (colors) of light. Besides, systems are already using fiber optic amplifiers as repeaters also do not require upgrading for most WDM.

From the above comparison of three methods for expanding capacity, it can easily draw a conclusion that WDM is the best solution to meet the demand for more capacity and faster data transmission rates. Actually, it is not difficult to understand the operating principle of WDM. Consider the factthat you can see many different colors of light: red, green, yellow, blue, etc. The colors are transmitted through the air together and may mix, but they can be easily separated by using a simple device like a prism. It’s like separating the “white” light from the sun into a spectrum of colors with the prism. WDM is equivalent to the prism in the operating principle. A WDM system uses a multiplexer at the transmitter to joint the several signals together. At the same time, it uses a demultiplexer at the receiver to split them apart, as shown in the following diagram. With the right type of fiber, it is possible to function as an optical add-drop multiplexer.

This technique was originally demonstrated with optical fiber in the early 80s. The first WDM systems combined only two signals. Modern systems can handle up to 160 signals and can thus expand a basic 10 Gbit/s system over a single fiber pair to over 1.6 Tbit/s.

Because WDM systems can expand the capacity of the network and accommodate several generations of technology development in optical infrastructure without having to overhaul the backbone network, they are popular with telecommunications companies.



CWDM VS DWDM

WDM systems are divided into different wavelength patterns: CWDM (Coarse Wavelength Division Multiplexing) and DWDM (Dense Wavelength Division Multiplexing). There are many differences between CWDM and DWDM: spacings, DFB lasers, and transmission distances. The channel spacings between individual wavelengths transmitted through the same fiber serve as the basis for defining CWDM and DWDM. Typically, the spacing in CWDM systems is 20 nm, while most DWDM systems today offer 0.8 nm (100 GHz) wavelength separation according to the ITU standard.

Due to wider CWDM channel spacing, the number of channels (lambdas) available on the same link is significantly reduced, but the optical interface components do not have to be as precise as DWDM components. CWDM equipment is thus significantly cheaper than DWDM equipment. Both CWDM and DWDM architectures utilize the DFB (Distributed Feedback Lasers). However, CWDM systems use DFB lasers that are not cooled. These systems typically operate from 0 to 70℃ with the laser wavelength drifting about 6 nm over this range. Coupled with the laser wavelength of up to ±3 nm, the wavelength drift yields a total wavelength variation of about ±12 nm.

DWDM systems, on the other hand, require the larger cooled DFB lasers, because a semiconductor laser wavelength drifts about 0.08 nm/℃ with temperature. DFB lasers are cooled to stabilize the wavelength from outside the passband of the multiplexer and demultiplexer filters as the temperature fluctuates in DWDM systems. Due to the unique attributes of CWDM and DWDM, they are deployed for different transmission distances. Typically, CWDM can travel anywhere up to about 160 km. If this needs to transmit the data over a long range, the DWDM system is the best choice. DWDM supports 1550 nm wavelength size, which can be amplified to extend transmission distance to hundreds of kilometers.

OPERATIONAL PRINCIPLES OF WDM

Since the spectral width of a high-quality source occupies only a narrow slice of optical bandwidth, there are many independent operating regions across the spectrum, ranging from the a-band through the L-band,that can be used simultaneously. The original use of WDM was to upgrade the capacity of installed point-to-point transmission links. This was achieved with wavelengths that were separated from several tens up to 200 nm in order not to impose strict wavelength-tolerance requirements on the different laser sources and the receiving wavelength splitters.

Subsequently, the development of lasers that have extremely narrow spectral emission widthsallowed wavelengths to be spaced less than a nanometer apart. This is the basis of wavelength- division multiplexing, which simultaneously uses a number of light sources, each emitting at a slightly different peak wavelength.

Each wavelength carries an independent signal, so that the link capacity is increased greatly. The main trick is to ensure that the peak wavelength of a source is spaced sufficiently far from its neighbor so as not to create interference between their spectral extents. Equally important is the requirement that during the operation of a system these peak wavelengths do not drift into thespectral territory occupied by adjacent channels. In addition to maintaining strict control of the wavelength, system designers include an empty guard band between the channels as an operations safety factor. Thereby the fidelities of the independent messages from each source are maintained forsubsequent conversion to electrical signals at the receiving end.

WDM Operating Regions

The possibility of having an extremely high-capacity link by means of WDM can be seen by examining the characteristics of a high-quality optical source. As an example, a distributed- feedback(DFB) laser has a frequency spectrum on the order of I MHz, which is equivalent to a spectral line width of 10-5 nm. With such spectral widths, simplex systems make use of only a tiny portion of the transmission bandwidth capability of a fiber. This can be seen from Figure which depicts the attenuation of light in a silica fiber as a function of wavelength. The curve shows that the two low- loss regions of a standard G.652 single-mode fiber extend over the O- band wavelengths rangingfrom about 1270 to 1350 nm (originally called the second window) and from 1480 to 1600nm (originally called the third window). This can view these regions either in terms of spectral width (the wavelength band occupied by the light signal) or by means of optical bandwidth (the frequency band occupied by the light signal).

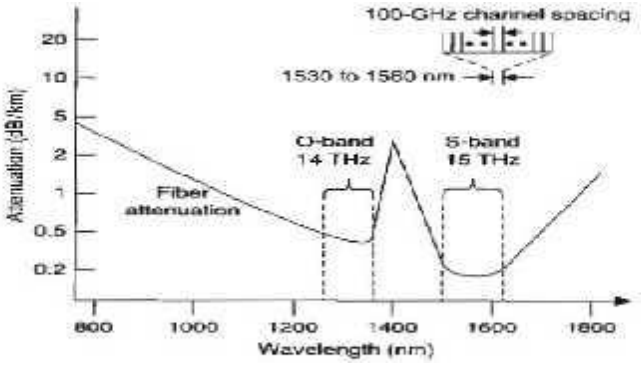


Figure Generic representation of attenuation of light in a silica fiber as a function of wavelength

To find the optical bandwidth corresponding to a particular spectral width in these regions, This uses the fundamental relationship c=Lamda*v, which relates the wavelength Laamda to the carrier frequency v, where c is the speed of light. Differentiating this,

$$\Delta\nu = \frac{c}{\lambda^2}\,\Delta\lambda$$

Where the frequency deviation corresponds to wavelength deviation around the wavelength

If fiber has the attenuation characteristic shown in Figure. The optical bandwidth is .Delta v= 14THz for a usable spectral band. Delta Lamda= 80 nm in the center of the O-band. Similarly, .Delta v= 15 THz for a usable spectral band Delta Lamda= 120 nm in the low-loss region running from near the beginning of the S-band to almost the end of the L-band. This yields a total available fiber bandwidth of about 30THz in the two low-loss windows.

Prior to about 2000, the peak wavelengths of adjacent light sources typically were restricted to be separated by 0.8 to 1.6 nm (100 to 200 GHz) in a WDM system. This was done to take into account possible drifts of the peak wavelength due to aging or temperature effects, and to give both the manufacturer and the user some leeway in specifying and choosing the precise peak emission wavelength. The next generation of WDM systems specified both narrower and much wider channel spacings depending on the application and on the wavelength region being used. The much narrower spacings thus require strict wavelength control of the optical source. On the other hand, the wider wavelength separations offer inexpensive WDM implementations since wavelength control requirements are relaxed significantly.

Generic WDM Link

The implementation of WDM networks requires a variety of passive and/or active devices to combine, distribute, isolate, add, drop, attenuate, and amplify optical power at different wavelengths. Passive devices require no external electric power or control for their operation, so they have a fixed application in WDM networks. These passive components are used to separate and combine wavelength channels, to divide optical power onto a number of fiber lines, or to tap off part of an optical signal for monitoring purposes. The performance of active devices can be controlled electronically, thereby providing a large degree of network flexibility, Active WDM components include tunable optical filters, tunable light sources, configurable add/drop multiplexers, dynamic gain equalizers, and optical amplifiers.

The transmitting side has a series of independently modulated fixed-wavelength light sources, eachof which emits signals at a unique wavelength. Here a multiplexer (popularly called a mux) is neededto combine these optical outputs into a continuous spectrum of signals and couple them onto a single fiber. Within a standard telecommunication link there may be various types of optical amplifiers, a variety of specialized active components (not shown), and passive optical power splitters. The operations and maintenance benefits of PONs are that no active devices are used between the transmitting and receiving endpoints.

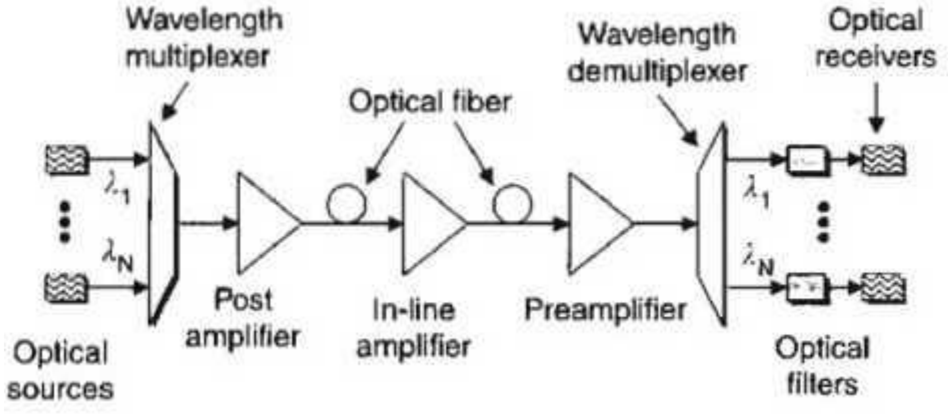


Figure Implementation of a simple WDM link

At the receiving end a demultiplexer is required to separate the individual wavelengths of the independent optical signals into appropriate detection channels for signal processing. At the transmitter the basic design challenge is to have the multiplexer provide a low-loss path from each optical source to the multiplexer output. A different requirement exists for the demultiplexer, since photodetectors usually are sensitive over a broad range of wavelengths, which could include all the WDM channels. To prevent spurious signals from entering a receiving channel, that is, to give good channel isolation of the different wavelengths being used, the demultiplexer must exhibit narrow spectral operation or very stable optical filters with sharp wavelength cutoffs must be used.

The tolerable crosstalk levels between channels can vary widely depending on the application. In general, a -10 dB level is not sufficient, whereas a level of - 30 dB is acceptable. In principle, any optical demultiplexer can also be used as a multiplexer. For simplicity, the word multiplexer is used as a general term to refer to both combining and separating functions, except when it is necessary to distinguish the two devices or functions.

Wavelength Division Multiplexing (WDM)

Optical signals of different wavelength (1300-1600 nm) can propagate without interfering with each other. The scheme of combining a number of wavelengths over a single fiber is called wavelength division multiplexing (WDM). Each input is generated by a separate optical source with a unique wavelength. Optical multiplexer couples light from individual sources to the transmitting fiber. At the receiving station, an optical demultiplexer is required to separate the different carriers before photodetection of individual signals. To prevent spurious signals to enter into receiving channel, the demultiplexer must have narrow spectral operation with sharp wavelength cut-offs. The acceptable limit of crosstalk is – 30 dB.

Features of WDM

- ❖ Capacity upgrade: Since each wavelength supports independent data rate in Gbps.
- ❖ Transparency: WDM can carry fast asynchronous, slow synchronous, synchronous analog and digital data.

- Wavelength routing: Link capacity and flexibility can be increased by using multiple wavelength.
- Wavelength switching: WDM can add or drop multiplexers, cross connects and wavelength converters.

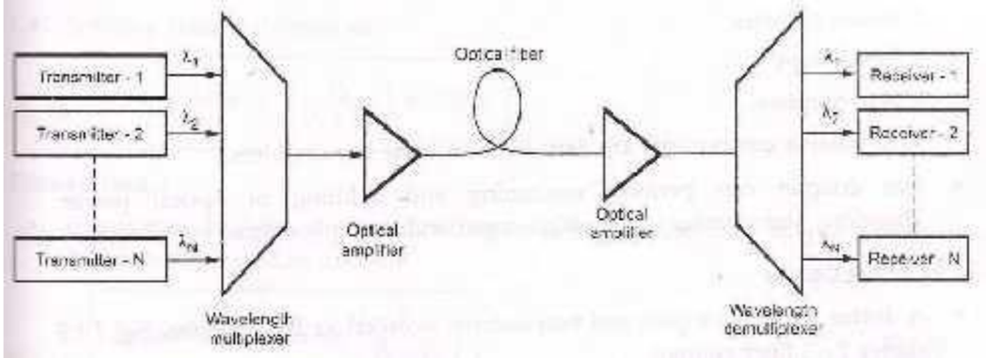


Figure WDM scheme

Passive Components

For implementing WDM various passive and active components are required to combine, distribute, isolate and to amplify optical power at different wavelength. Passive components are mainly used to split or combine optical signals. These components operate in optical domains. Passive components don't need external control for their operation. Passive components are fabricated by using optical fibers by planar optical waveguides. Commonly required passive components are

- N x N couplers
- Power splitters
- Power taps
- Star couplers.

Most passive components are derived from basic stat couplers. Star coupler can person combining and splitting of optical power. Therefore, star coupler is a multiple input and multiple output port device.

Dense Wavelength Division Multiplexing (DWDM)

- DWDM (Dense wavelength – division multiplexing) is a data transmission technology having very large capacity and efficiency.
- Multiple data channels of optical signals are assigned different wavelengths, and are multiplexed onto one fiber.
- DWDM system consists of transmitters, multiplexers, optical amplifier and demultiplexer.

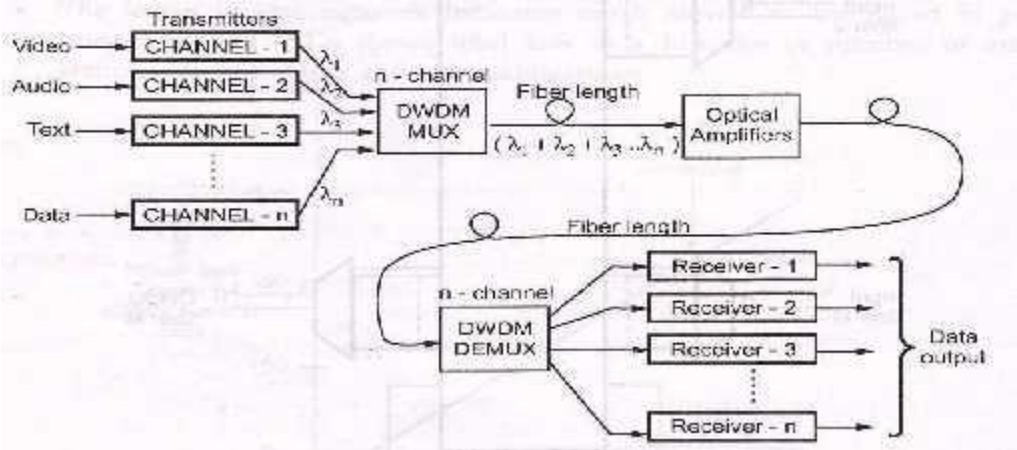


Figure DWDM System

- DWDM used single mode fiber to carry multiple light waves of different frequencies.
- DWDM system uses Erbium – Doped Fiber Amplifiers (EDFA) for its long haul applications, and to overcome the effects of dispersion and attenuation channel spacing of 100 GHz is used.

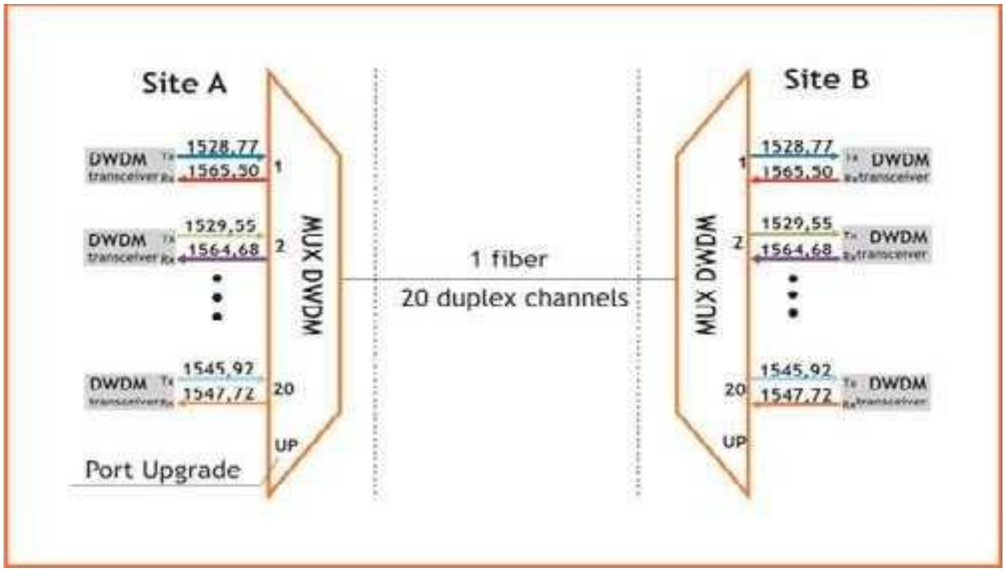
DWDW is short for dense wavelength division multiplexing. It is an optical multiplexing technology used to increase bandwidth over existing fiber networks. DWDM works by combining and transmitting multiple signals simultaneously at different wavelengths on the same fiber. It has revolutionized the transmission of information over long distances. DWDM can be divided into passive DWDM and active DWDM. This article will detail these two DWDM systems.

Passive DWDM

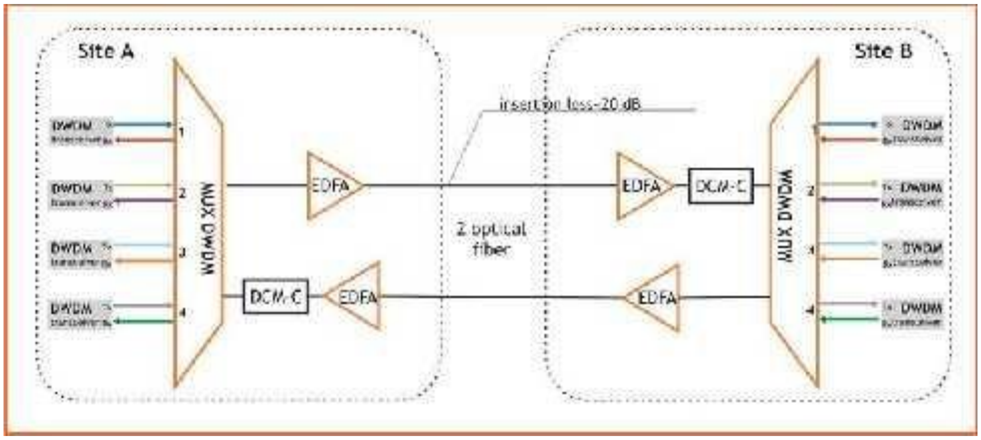
Passive DWDM systems have no active components. The line functions only due to the optical budget of transceivers used. No optical signal amplifiers and dispersion compensators are used. Passive DWDM systems have a high channel capacity and potential for expansion, but the transmission distance is limited to the optical budget of transceivers used. The main application of passive DWDM system is metro networks and high speed communication lines with a high channel capacity.

Active DWDM

Active DWDM systems commonly refer to as a transponder-based system. They offer a way to transport large amounts of data between sites in a data center interconnect setting. The transponder takes the outputs of the SAN or IP switch format, usually in a short wave 850nm or long wave 1310nm format, and converts them through an optical-electrical-optical (OEO) DWDM conversion. When creating long-haul DWDM networks, several EDFA amplifiers are installed sequentially in the line. The number of amplifiers in one section is limited and depends on the optical cable type, channel count, data transmission rate of each channel, and permissible OSNR value.



The possible length of lines when using active DWDM system is determined not only with installed optical amplifiers and the OSNR value, but also with the influence of chromatic dispersion—the distortion of transmitted signal impulses, on transmitted signals. At the design stage of the DWDM network project, permissible values of chromatic dispersion for the transceivers are taken into account, and, if necessary, chromatic dispersion compensation modules (DCM) are included in the line. DCM introduces additional attenuation into the line, which leads to a reduction of the amplified section length. At this stage, a basic DWDM system contains several main components:



WDM multiplexer for DWDM communications

DWDM terminal multiplexer- The terminal multiplexer contains a wavelength- converting transponder for each data signal, an optical multiplexer and where necessary an optical amplifier (EDFA). Each wavelength-converting transponder receives an optical data signal from the client-layer, such as Synchronous optical networking [SONET /SDH] or another type of data signal, converts this signal into the electrical domain and re- transmits the signal at a specific wavelength using a 1,550 nm band laser. These data signals are then combined together into a multi-wavelength optical signal using an optical multiplexer, for transmission over a single fiber (e.g., SMF-28 fiber).

The terminal multiplexer may or may not also include a local transmit EDFA for power amplification of the multi-wavelength optical signal. In the mid-1990s DWDM systems contained 4 or 8 wavelength-converting transponders; by 2000 or so, commercial systems capable of carrying 128 signals were available.

An intermediate line repeater is placed approximately every 80–100 km to compensate for the loss of optical power as the signal travels along the fiber. The 'multi-wavelength optical signal' is amplified by an EDFA, which usually consists of several amplifier stages. An intermediate optical terminal, or optical add-drop multiplexer. This is a remote amplification site that amplifies the multi-wavelength signal that may have traversed up to 140 km or more before reaching the remote site. Optical diagnostics and telemetry are often extracted or inserted at such a site, to allow for localization of any fiber breaks or signal impairments.

In more sophisticated systems (which are no longer point-to-point), several signals out of the multi-wavelength optical signal may be removed and dropped locally. A DWDM terminal demultiplexer at the remote site, the terminal de-multiplexer consisting of an optical de- multiplexer and one or more wavelength-converting transponders separates the multi-wavelengthoptical signal back into individual data signals and outputs them on separate fibers for client-layer systems. Originally, this de-multiplexing was performed entirely passively, except for some telemetry, as most SONET systems can receive 1,550 nm signals.

However, in order to allow for transmission to remote client-layer systems (and to allow for digital domain signal integrity determination) such de-multiplexed signals are usually sent to O/E/O output transponders prior to being relayed to their client-layer systems. Often, the functionality of output transponder has been integrated into that of input transponder, so that most commercial systems have transponders that support bi-directional interfaces on both their 1,550 nm (i.e., internal) side, and external (i.e., client-facing) side. Transponders in some systems supporting 40 GHz nominal operation may also perform forward error correction (FEC) via digital wrapper technology, as described in the ITU-T G.709 standard.

Optical Supervisory Channel (OSC). This is data channel which uses an additional wavelength usually outside the EDFA amplification band (at 1,510 nm, 1,620 nm, 1,310 nm or another proprietary wavelength). The OSC carries information about the multi-wavelength optical signal as well as remote conditions at the optical terminal or EDFA site. It is also normally used for remote software upgrades and user (i.e., network operator) Network Management information. It is the multi-wavelength analogue to SONET's DCC (or supervisory channel). ITU standards suggest that the OSC should utilize an OC-3 signal structure, though some vendors have opted to use 100 megabit Ethernet or another signal format. Unlike the 1550 nm multi-wavelength signal containing client data, the OSC is always terminated at intermediate amplifier sites, where it receives local information before re-transmission.

Erbium-Doped Fiber Amplifiers

An important class of fiber amplifiers makes use of rare-earth elements as a gain medium by doping the fiber core during the manufacturing process. Although doped-fiber amplifiers were studied as early as 1964, their use became practical only 25 years later, after the fabrication and characterization techniques were perfected. Amplifier properties such as the operatingwavelength and the gain bandwidth are determined by the dopants rather than by the silica fiber, which plays the role of a host medium. Many different rare-earth elements, such as erbium, holmium, neodymium, samarium, thulium, and ytterbium, can be used to realize fiber amplifiers operating at different wavelengths in the range 0.5–3.5 μm.

Erbium-doped fiber amplifiers (EDFAs) have attracted the most attention because they operate in the wavelength region near 1.55 μm. Their deployment in WDM systems after 1995 revolutionized the field of fiber-optic communications and led to light wave systems with capacities exceeding 1 Tb/s. This section focuses on the main characteristics of EDFAs.

Pumping Requirements

The design of an EDFA looks similar to that in Figure with the main difference that the fiber core contains erbium ions (Er^{3+}). Pumping at a suitable wavelength provides gain throughpopulation inversion. The gain spectrum depends on the pumping scheme as well as on the presence of other dopants, such as germania and alumina, within the fiber core.

The amorphous nature of silica broadens the energy levels of Er^{3+} into bands. Figure (a) shows a few energy levels of Er^{3+} in silica glasses. Many transitions can be used to pump an EDFA. Early experiments used the visible radiation emitted from argon-ion, Nd:YAG, or dye lasers even though such pumping schemes are relatively inefficient. From a practical standpoint the use of semiconductor lasers is preferred.

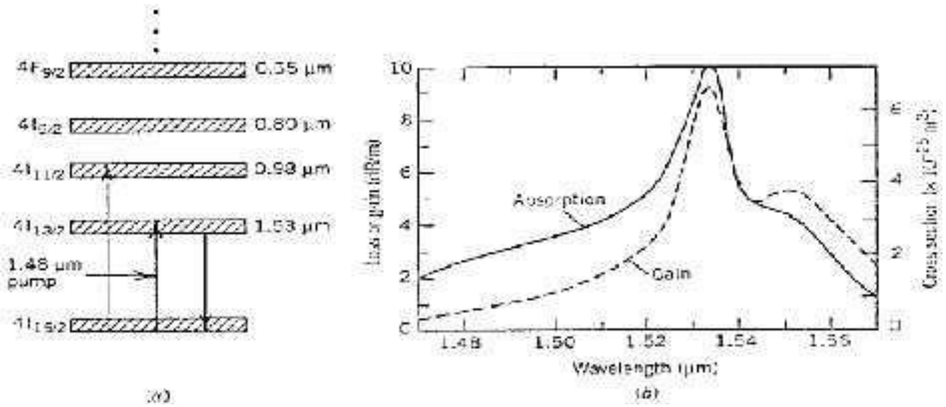


Figure (a) Energy-level diagram of erbium ions in silica fibers; (b) absorption and gain spectra of an EDFA whose core was co doped with germania

Efficient EDFA pumping is possible using semiconductor lasers operating near 0.98 and 1.48μm wavelengths. Indeed, the development of such pump lasers was fueled with the advent ofEDFAs. It is possible to realize 30-dB gain with only 10–15 mW of absorbed pump power. Efficiencies as high as 11 dB/mW were achieved by 1990 with 0.98-μmpumping. The pumping transition 4I15/2→ 4I9/2 can use high power GaAs lasers, and the pumping efficiency of about 1dB/mW has been obtained at 820 nm. The required pump power can be reduced by using silica fibers doped with aluminum and phosphorus or by using fluorophosphate fibers. With theavailability of visible semiconductor lasers, EDFAs can also be pumped in the wavelength range 0.6–0.7 μm. In one experiment, 33-dB gain was realized at 27mW of pump power obtained from an AlGaInP laser operating at 670 nm. The pumping efficiency was as high as 3 dB/mW at low pump powers. Most EDFAs use 980-nm pump lasers as such lasers are commercially available and can provide more than 100 mW of pump power. Pumping at 1480 nm requires longer fibers and higher powers because it uses the tail of the absorption band shown in Figure.

EDFAs can be designed to operate in such a way that the pump and signal beams propagate in opposite directions, a configuration referred to as backward pumping to distinguish it from the forward-pumping configuration shown in Figure. The performance is nearly the same in the two pumping configurations when the signal power is small enough for the amplifier to remain unsaturated.

In the saturation regime, the power-conversion efficiency is generally better in the backward-pumping configuration, mainly because of the important role played by the amplified spontaneous emission (ASE). In the bidirectional pumping configuration, the amplifier is pumped in both directions simultaneously by using two semiconductor lasers located at the two fiber ends. This configuration requires two pump lasers but has the advantage that the populationinversion, and hence the small-signal gain, is relatively uniform along the entire amplifier length.

The foregoing analysis assumes that both pump and signal waves are in the form of CW beams. In practice, EDFAs are pumped by using CW semiconductor lasers, but the signal is in the form of a pulse train (containing a random sequence of 1 and 0 bits), and the duration of individual pulses is inversely related to the bit rate.

The question is whether all pulses experience the same gain or not. As discussed the gain of each pulse depends on the preceding bit pattern for SOAs because an SOA can respond on time scales of 100 ps or so. Fortunately, the gain remains constant with time in an EDFA for even microsecond-long pulses. The reason is related to a relatively large value of the fluorescence time associated with the excited erbium ions ($T_1 \sim 10$ ms). When the time scale of signal-power variations is much shorter than T_1, erbium ions are unable to follow such fast variations. As single-pulse energies are typically much below the saturation energy (∼10 μJ), EDFAs respondto the average power. As a result, gain saturation is governed by the average signal power, and amplifier gain does not vary from pulse to pulse even for a WDM signal.

In some applications such as packet-switched networks, signal power may vary on a time scale comparable to *T*1. Amplifier gain in that case is likely to become time dependent, an undesirable feature from the standpoint of system performance. A gain control mechanism that keeps the amplifier gain pinned at a constant value consists of making the EDFA oscillate at a controlled wavelength outside the range of interest (typically below 1.5 μm). Since the gain remains clamped at the threshold value for a laser, the signal is amplified by the same factor despite variations in the signal power. In one implementation of this scheme, an EDFA was forced to oscillate at 1.48 μm by fabricating two fiber Bragg gratings acting as high-reflectivity mirrors at the two ends of the amplifier.

Multichannel Amplification

The bandwidth of EDFAs is large enough that they have proven to be the optical amplifier of choice for WDM applications. The gain provided by them is nearly polarization insensitive. Moreover, the interchannel crosstalk that cripples SOAs because of the carrier-density modulation occurring at the channel spacing does not occur in EDFAs. The reason is related to the relatively large value of *T*1 (about 10 ms) compared with the carrier lifetime in SOAs (<1 ns). The sluggish response of EDFAs ensures that the gain cannot be modulated at frequencies much larger than 10 kHz.

A second source of interchannel crosstalk is cross-gain saturation occurring because the gain of a specific channel is saturated not only by its own power (self saturation) but also by the power of neighboring channels. This mechanism of crosstalk is common to all optical amplifiers including EDFAs. It can be avoided by operating the amplifier in the unsaturated regime. Experimental results support this conclusion. In a 1989 experiment negligible power penalty was observed when an EDFA was used to amplify two channels operating at 2 Gb/s and separated by 2 nm as long as the channel powers were low enough to avoid the gain saturation. The main practical limitation of an EDFA stems from the spectral non uniformity of the amplifier gain. Even thoughthe gain spectrum of an EDFA is relatively broad, as seen in Figure, the gain is far from uniform (or flat) over a wide wavelength range. As a result, different channels of a WDM signal are amplified by different amounts.

This problem becomes quite severe in long-haul systems employing a cascaded chain of EDFAs. The reason is that small variations in the amplifier gain for individual channels grow exponentially over a chain of in-line amplifiers if the gain spectrum is the same for all amplifiers.Even a 0.2-dB gain difference grows to 20 dB over a chain of 100 in-line amplifiers, making channel powers vary by a factor of 100, an unacceptable variation range in practice. To amplify all channels by nearly the same amount, the double-peak nature of the EDFA gain spectrum forces one to pack all channels near one of the gain peaks. In a simple approach, input powers of different channels were adjusted to reduce power variations at the receiver to an acceptable level.

This technique may work for a small number of channels but becomes unsuitable for dense WDM systems.

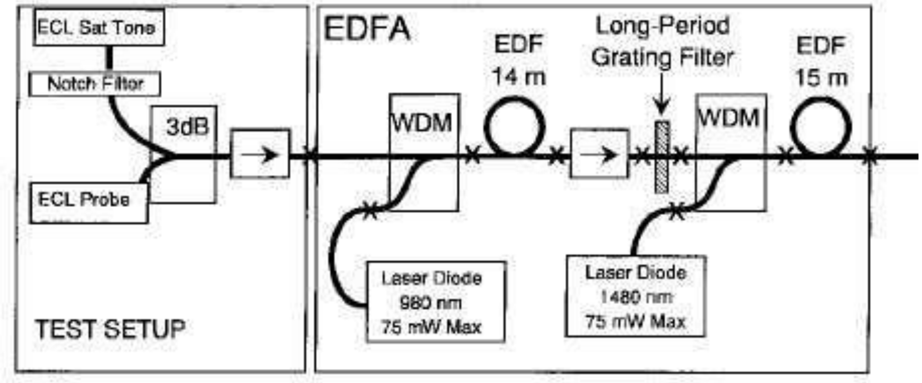


Figure Schematic of an EDFA designed to provide uniform gain over the 1530–1570- nm bandwidth using an optical filter containing several long-period fiber gratings. The two stage design helps to reduce the noise level.

The entire bandwidth of 35–40 nm can be used if the gain spectrum is flattened by introducing wavelength-selective losses through an optical filter. The basic idea behind gain flattening is quite simple. If an optical filter whose transmission losses mimic the gain profile (high in the high-gain region and low in the low-gain region) is inserted after the doped fiber, the output power will become constant for all channels. Although fabrication of such a filter is not simple, several gain-flattening techniques have been developed. For example, thin-film interference filters, Mach–Zehnder filters, acousto-optic filters, and long-period fiber gratings have been usedfor flattening the gain profile and equalizing channel gains .

The gain-flattening techniques can be divided into active and passive categories. Most filter- based methods are passive in the sense that channel gains cannot be adjusted in a dynamic fashion. The location of the optical filter itself requires some thought because of high losses associated with it. Placing it before the amplifier increases the noise while placing it after the amplifier reduces the output power. Often a two-stage configuration shown in Figure is used.The second stage acts as a power amplifier while the noise figure is mostly determined by the first stage whose noise is relatively low because of its low gain. A combination of several long- period fiber gratings acting as the optical filter in the middle of two stages resulted by 1977 in anEDFA whose gain was flat to within 1 dB over the 40-nm bandwidth in the wavelength range of 1530–1570 nm.

Ideally, an optical amplifier should provide the same gain for all channels under all possible operating conditions. This is not the case in general. For instance, if the number of channels being transmitted changes, the gain of each channel will change since it depends on the total signal power because of gain saturation.

The active control of channel gains is thus desirable for WDM applications. Many techniques have been developed for this purpose. The most commonly used technique stabilizes the gain dynamically by incorporating within the amplifier a laser that operates outside the used bandwidth. Such devices are called gain-clamped EDFAs (as their gain is clamped by a built-in laser) and have been studied extensively.

WDM light wave systems capable of transmitting more than 80 channels appeared by 1998. Such systems use the C and L bands simultaneously and need uniform amplifier gain over a bandwidth exceeding 60 nm. Moreover, the use of the L band requires optical amplifiers capable of providing gain in the wavelength range 1570–1610 nm. It turns out that EDFAs can provide gain over this wavelength range, with a suitable design. An L-band EDFA requires long fiber lengths (>100 m) to keep the inversion level relatively low. Figure shows an L-band amplifier with a two-stage design.

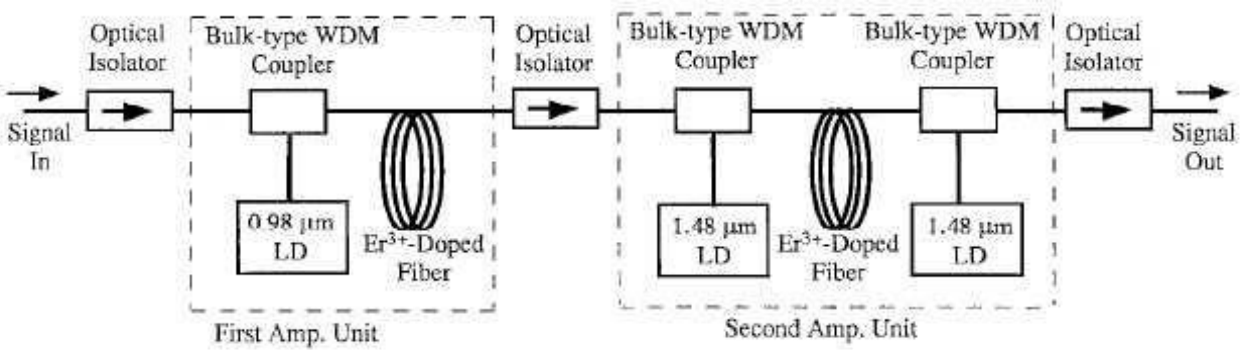


Figure Schematic of an L-band EDFA providing uniform gain over the 1570–1610-nm bandwidth with a two-stage design

The first stage is pumped at 980 nm and acts as a traditional EDFA (fiber length 20–30 m) capable of providing gain in the range 1530–1570 nm. In contrast, the second stage has 200-m- long doped fiber and is pumped bidirectionally using 1480-nm lasers. An optical isolator between the two stages passes the ASE from the first stage to the second stage (necessary for pumping the second stage) but blocks the backward propagating ASE from entering the first stage. Such cascaded, two-stage amplifiers can provide flat gain over a wide bandwidth while maintaining a relatively low noise level. As early as 1996, flat gain to within 0.5 dB was realized over the wavelength range of 1544–1561 nm.

The second EDFA was co doped with ytterbium and phosphorus and was optimized such that it acted as a power amplifier. Since then, EDFAs providing flat gain over the entire C and L bands have been made. Raman amplification can also be used for the L band. Combining Raman amplification with one or two EDFAs, uniform gain can be realized over a 75nm bandwidth covering the C and L bands. A parallel configuration has also been developed for EDFAs capable of amplifying over the C and L bands simultaneously.

In this approach, the incoming WDM signal is split into two branches, which amplify the C-band and L-band signals separately using an optimized EDFA in each branch. The two-arm design has produced a relatively uniform gain of 24 dB over a bandwidth as large as 80 nm when pumped with 980-nm semiconductor lasers while maintaining a noise figure of about 6 dB.

The two-arm or two-stage amplifiers are complex devices and contain multiple components, such as optical filters and isolators, within them for optimizing the amplifier performance. An alternative approach to broadband EDFAs uses a fluoride fiber in place of silica fibers as the host medium in which erbium ions are doped. Gain flatness over a 76-nm bandwidth has been realized by doping a tellurite fiber with erbium ions. Although such EDFAs are simpler in designcompared with multistage amplifiers, they suffer from the splicing difficulties because of the use of non silica glasses. Starting in 2001, high-capacity light wave systems began to use the short- wavelength region the so-called S band extending from 1470 to 1520 nm.

Optical CDMA

In OCDMA, each user has a unique code as an assignment address that spreads over a relatively wide bandwidth. This specific code is modulated and then a message signal is transmitted at an arbitrary time to an intended receiver, which can match the correct code to recover the encoded information. The principle of OCDMA multiplexing leads to support of a larger channel count than other techniques, allows asynchronous transmission with efficient access and enhances information security potentially in the network.

Furthermore, it has employment of simplified network control and management, multi-class traffic with different formats and bit rates and can be easily upgraded in terms of its architecture. Each user has been assigned to some chips of the code sequences to share the same transmission line using power splitters or combiners. This operation can be performed in the optical-domain and/or in the space-domain as well.

Decoders at the receiver recognize a target code by employing match filtering. Six types of coding

Direct-sequence or temporal coding optical CDMA systems

- Spectral Amplitude Coding (SAC) Optical CDMA systems
- Spectral Phase Coding (SPC) optical CDMA systems
- Temporal phase coding optical CDMA systems;
- Two-Dimensional (2-D) spatial or spread space coding optical CDMA systems
- Hybrid coding optical CDMA systems

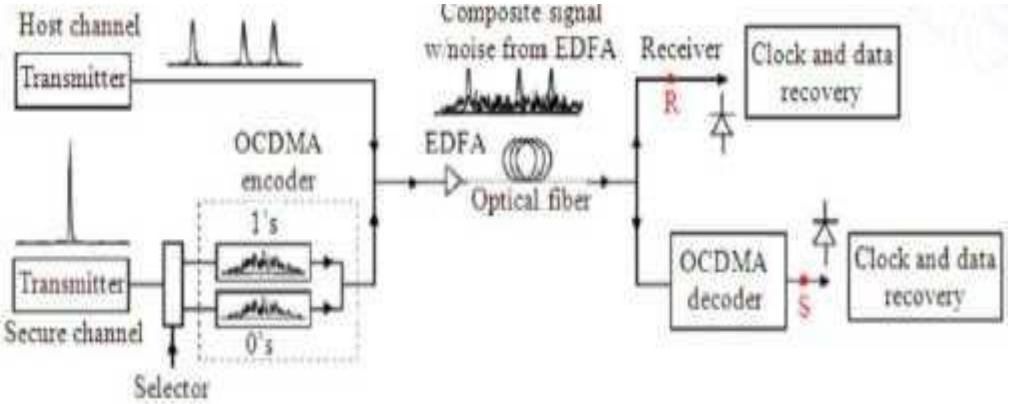


Figure Hybrid System

Two signals are used as shown in figure, a secure signal is encoded and temporally spread to be hidden under a host channel. The purpose of the host channel in this scheme is to provide an ad hoc security enhancement for an encoded signal. The OCDMA en/decoder consists of a coherent spectral phase with direct detection.

Solitons:

Solitons are narrow pulses with high peak powers and special shapes. The most commonly used soliton pulses are called fundamental solitons. The shape of these pulses is shown in Figure. The soliton pulses take advantage of nonlinear effects in silica, specifically self-phase modulation, to overcome the pulse-broadening effects of group velocity dispersion. These pulses can propagate for long distances with no change in shape.

The pulse shapes for which this balance between pulse compression and broadening occurs so that the pulse either undergoes no change in shape or undergoes periodic changes in shape only are called solitons. The family of pulses that undergo no change in shape are called fundamental solitons, and those that undergo periodic changes in shape are called higher-order solitons.

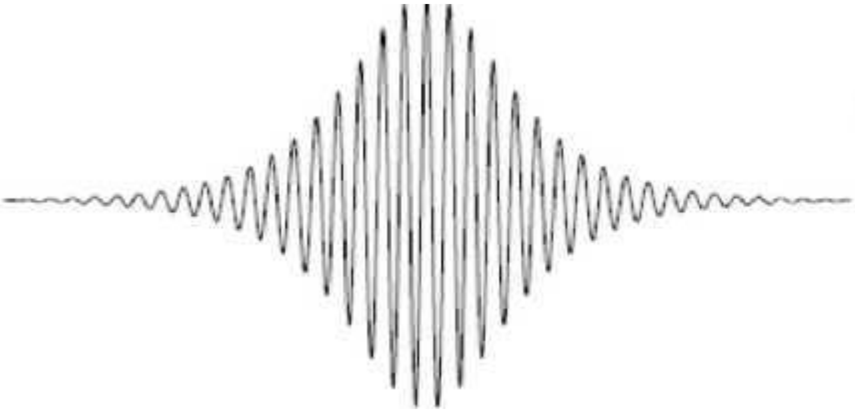


Figure soliton pulse -envelope

The significance of solitons for optical communication is that they overcome the detrimental effects of chromatic dispersion completely Solitons and optical amplifiers, when used together, offer the promise of very high-bit- rate, repeaterless data transmission over very large distances. By the combined use of solitons and erbium-doped fiber amplifiers repeaterless data transmission at a bit rate of 80 Gb/s over a distance of 10,000 km.

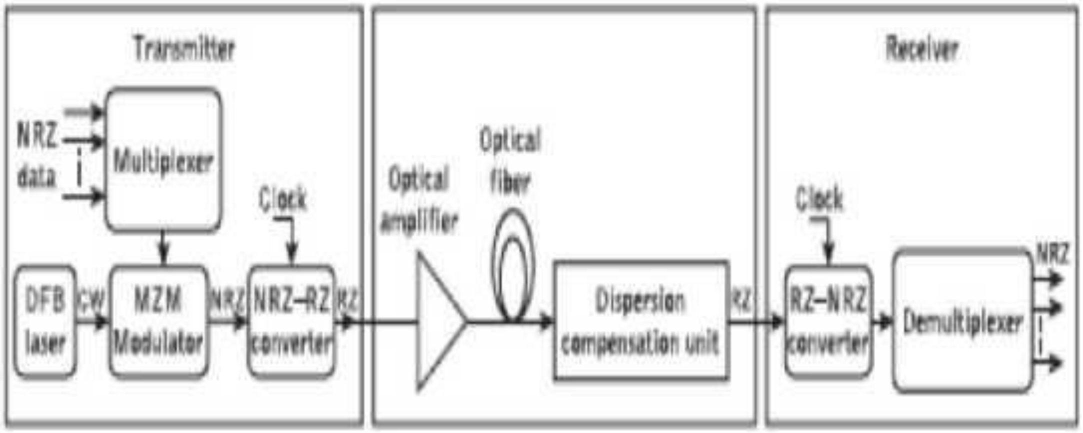


Figure Block schematic of optical fiber soliton transmission system

The use of soliton pulses is key to realizing the very high bit rates required in OTDM systems. The main advantage of soliton systems is their relative immunity to fiber dispersion, which in turn allows transmission at high speeds of a few tens of gigabits per second. The major elementin the transmitter section is a return-to-zero pulse generator. A simple approach to generate RZ pulses is to employ an optical modulator and an NRZ-to-RZ converter which is driven by a DFB laser source.

Instead of using a single NRZ data stream, however, it is useful to modulate an optical NRZ signal incorporating several multiplexed NRZ data streams before the conversion into RZ pulses takes place. At the receiving end the incoming signal requires conversion back from RZ to NRZ and then finally a demultiplexer separates the specific NRZ data for each channel. The transmission bit rate of a soliton communication system is dependent on mainly two factors: namely, the soliton pulse width τ and the duration of the bit period to

$$B_T = 1/T_o = 1/2qo\tau$$

$$qo = T_o / 2\tau$$

The ratio of T_o / τ determines the nature of the nonlinear propagation for soliton pulses.

Ultra High Capacity Networks

In long haul transmission links the capacity can be improved by ultrafast optical TDM scheme. Two forms of optical TDM schemes are used. Bit interleaved optical TDM, packet interleaved TDM. Optical signals representing data streams from multiple sources are interleaved in time to produce a single data stream. The interleaving can be done on a bit-by-bit basis as shown in Figure

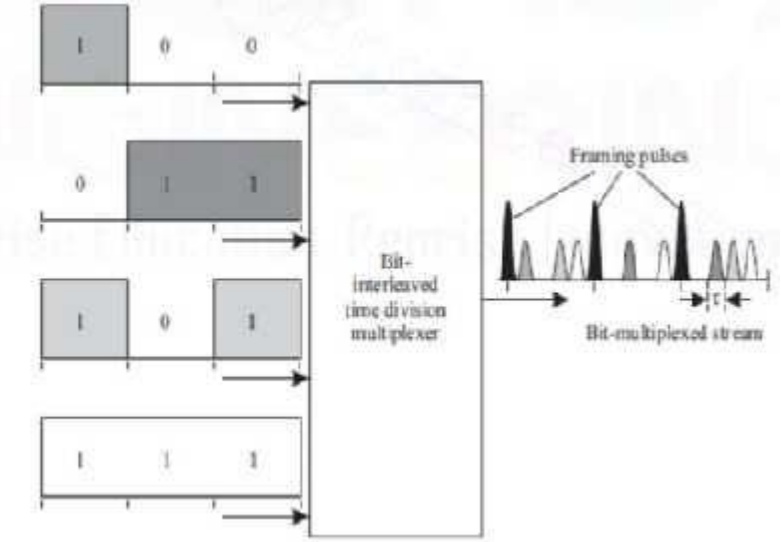


Figure Bit interleaved optical TDM

In the bit-interleaved case, if n input data streams are to be multiplexed, a framing pulse is used every n bits. The periodic pulse train generated by a mode-locked laser is split, and one copy is created for each data stream to be multiplexed. The pulse train for the ith data stream, i = 1, 2, . . .,n, is delayed by τ . This delay can be achieved by passing the pulse train through the appropriate length of optical fiber.

Thus the delayed pulse streams are non overlapping in time. The undelayed pulse stream is used for the framing pulses. Each data stream is used to externally modulate the appropriately delayed periodic pulse stream. The outputs of the external modulator and the framing pulse stream are combined to obtain the bit-interleaved optical TDM stream.

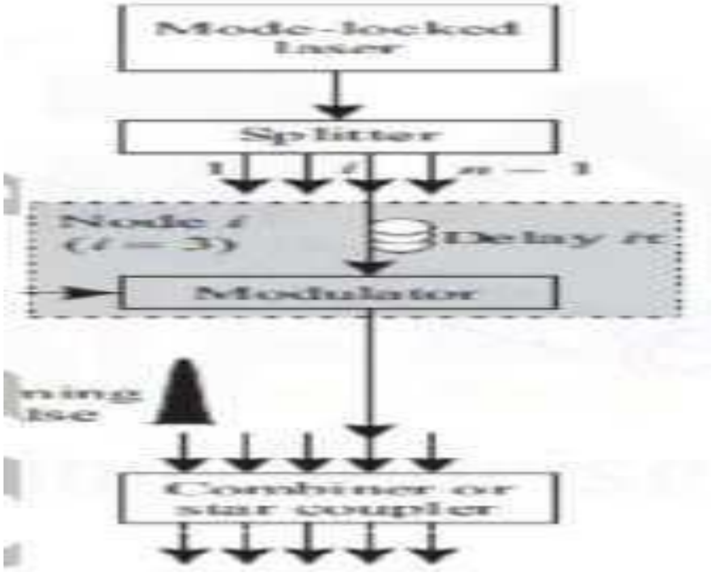


Figure optical multiplexer to create nit interleaved TDM Stream Since the velocity of light in silica fiber is about 2 × 108 m/s, 1 meter of fiber provides a delay of about 5 ns.

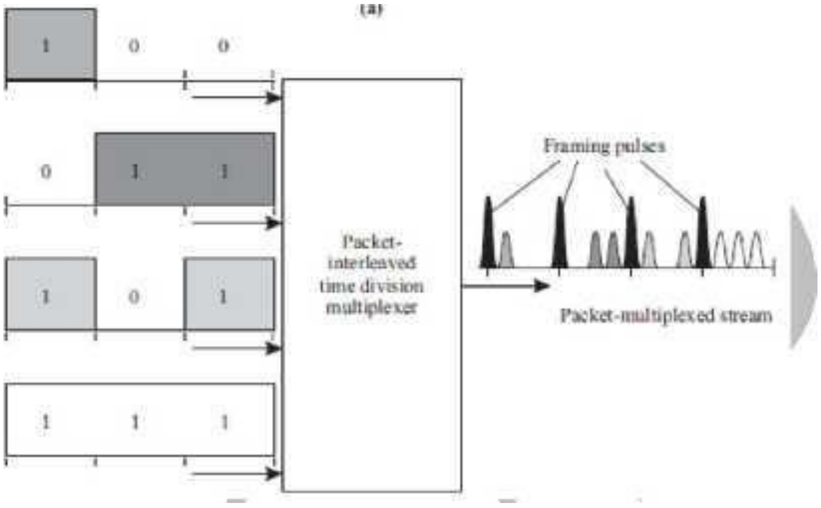
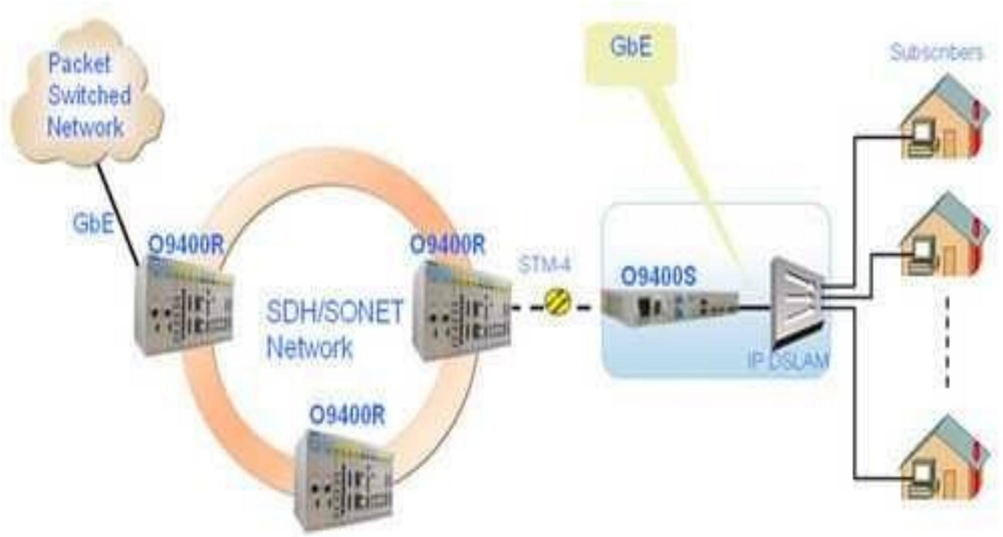


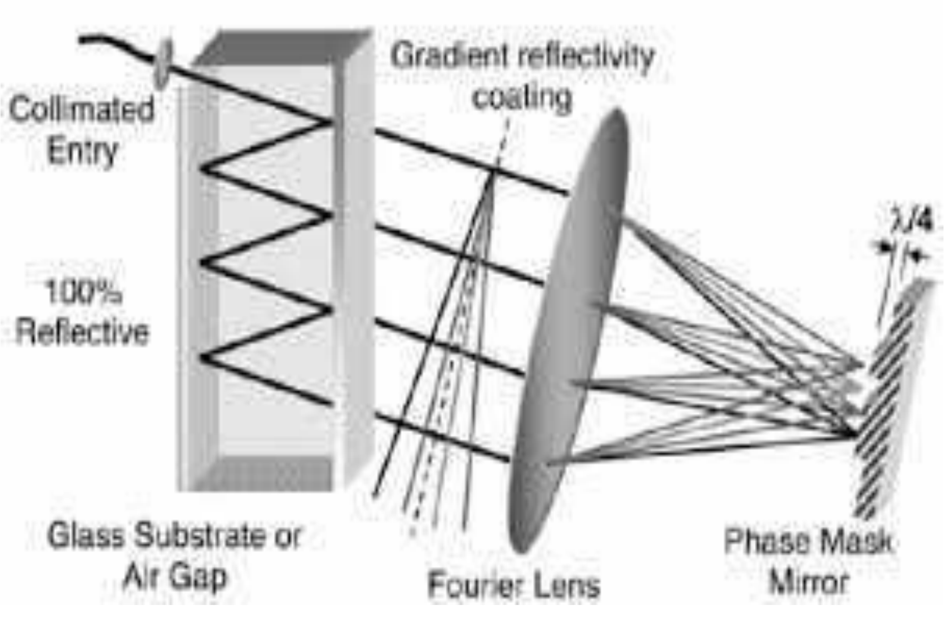
Figure packet interleaved optical TDM

In both the bit-interleaved and the packet-interleaved case, framing pulses can be used In the packet-interleaved case, framing pulses mark the boundary between packets. The j th compression stage is shown in Figure Each compression stage consists of a pair of 3 dB couplers, two semiconductor optical amplifiers (SOAs) used as on-off switches, and a delay line. the output pulses are separated by a time interval of τ .

APPLICATIONS



Examples of Remote Device Management & Optical SDH Application Distributor



Examples of Emerging Optical CDMA application