COURSE MATERIAL

OPTICAL COMMUNICATION

FOR

IV YEAR / VII SEMESTER

ACADEMIC YEAR 2021-22

BY

DR.K. ANITHA

ASSISTANT PROFESSOR

DEPARTMENT OF ELECTRONICS AND COMMUNICATION

SRI CHANDRASEKARENDRA VISWA MAHA VIDYALAYA
(SCSVMV)
(Deemed to be university u/s 3 of the UGC Act 1956)
(Accredited ‘A’ Grade by NAAC)
ENATHUR, KANCHIPURAM – 631 561.

PCC27 OPTICAL COMMUNICATION VII SEMESTER

OBJECTIVE:

- **To learn the basic elements of optical fiber transmission link, fiber modes configurations and structures.**
- **To understand the different kind of losses, signal distortion, SM fibers. To learn the various optical sources, materials and fiber splicing**
- **To learn the fiber optical receivers and noise performance in photo detector.**
- **To explore link budget, WDM, solitons and SONET/SDH network**

UNIT I INTRODUCTION TO OPTICAL FIBERS

Evolution of fiber optic system- Element of an Optical Fiber Transmission link-- Total internal reflection-Acceptance angle –Numerical aperture – Skew rays Ray Optics-Optical Fiber Modes and Configurations -Mode theory of Circular Wave guides-Overview of Modes-Key Modal Concepts-Linearly Polarized Modes -Single Mode Fibers-Graded Index fiber structure

UNIT II SIGNAL DEGRADATION OPTICAL FIBERS

Attenuation - Absorption losses, Scattering losses, Bending Losses, Core and Cladding losses, Signal Distortion in Optical Waveguides-Information Capacity determination - Group Delay- Material Dispersion, Wave guide Dispersion, Signal distortion in SM fibers-Polarization Mode dispersion, Intermodal dispersion, Pulse Broadening in GI fibers-Mode Coupling -Design Optimization of SM fibers-RI profile and cut-off wavelength.

UNIT III FIBER OPTICAL SOURCES AND COUPLING

Direct and indirect Band gap Materials -LED structures -Light source materials - Quantum efficiency and LED power, Modulation of a LED, lasers Diodes-Modes and Threshold condition – Rate equations-External Quantum efficiency -Resonant frequencies -Laser Diodes, Temperature effects, Introduction to Quantum laser, Fiber amplifiers- Power Launching and coupling, Lencing schemes, Fiber -to- Fiber joints, Fiber splicing-Signal to Noise ratio , Detector response time.

UNIT IV FIBER OPTIC RECEIVER AND MEASUREMENTS

Fundamental receiver operation, Pre-amplifiers, Error sources – Receiver Configuration– Probability of Error –Quantum limit, Fiber Attenuation measurements- Dispersion measurements – Fiber Refractive index profile measurements – Fiber cut- off Wave length Measurements – Fiber Numerical Aperture Measurements – Fiber diameter measurements

UNIT V OPTICAL NETWORKS AND SYSTEM TRANSMISSION

Basic Networks – SONET / SDH – Broadcast – and –select WDM Networks –Wavelength Routed Networks – Non linear effects on Network performance —Link Power budget - Rise time budget-Noise Effects on System Performance- Operational Principles of WDM Performance of WDM + EDFA system – Solutions – Optical CDMA – Solitons in Optical Fiber -Ultra High Capacity Networks.

OUTCOMES:

At the end of the course, the student should be able to:

1. **Demonstrate an understanding of optical fiber communication link, structure, propagation and transmission properties of an optical fiber.**
2. **Estimate the losses and analyze the propagation characteristics of an optical signal in different types of fibers.**
3. **Describe the principles of optical sources and power launching-coupling methods.**
4. **Compare the characteristics of fiber optic receivers.**
5. **Design a fiber optic link based on budgets To assess the different techniques to improve the capacity of the system.**

TEXT BOOKS:

1. **Gerd Keiser, “Optical Fiber Communication & quot; Mc Graw-Hill International, 4th Edition. 2010.**
2. **John M. Senior, “Optical Fiber Communication”, Second Edition, Pearson Education, 2007.**

REFERENCES:

1. **Ramaswami, Sivarajan and Sasaki “Optical Networks”, Morgan Kaufmann, 2009.**
2. **J.Senior, & quot; Optical Communication, Principles and Practice & quot;, Prentice Hall of India, 3^{rd} Edition, 2008.**
3. **J.Gower, & quot; Optical Communication System & quot;, Prentice Hall of India, 2001.**

UNIT I INTRODUCTION TO OPTICAL FIBERS

- **Evolution of fiber optic system**
- **Element of an Optical Fiber Transmission link**
- **Total internal reflection-Acceptance angle**
- **Numerical aperture**
- **Skew rays Ray Optics**
- **Optical Fiber Modes and Configurations**
- **Mode theory of Circular Wave guides**
- **Overview of Modes**
- **Key Modal Concepts**
- **Linearly Polarized Modes**
- **Single Mode Fibers**
- **Graded Index fiber structure**

UNIT I INTRODUCTION TO OPTICAL FIBERS

Introduction

• An optical Fiber is a thin, flexible, transparent Fiber that acts as a waveguide, or "light pipe", to transmit light between the two ends of the Fiber.

• Optical fibers are widely used in Fiber-optic communications, which permits transmission over longer distances and at higher bandwidths (data rates) than other forms of communication.

• Fibers are used instead of metal wires because signals travel along them with less loss and are also immune to electromagnetic interference.

Evolution of fiber optic system

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: 100 Mb/s to 1.7 Gb/s
ii) Repeater spacing: 50 km
iii) Operation wavelength: 1.3 μm
iv) Semiconductor: In GaAsP

Third generation

i) Bit rate: 10 Gb/s

ii) Repeater spacing: 100 km

iii) Operating wavelength: 1.55 μm

Fourth generation

• Fourth generation uses WDM technique.

i) Bit rate: 10 Tb/s
ii) Repeater spacing: > 10,000 km
iii) Operating wavelength: 1.45 to 1.62 μm

Fifth generation

• Fifth generation uses Roman amplification technique

and optical solitiors.

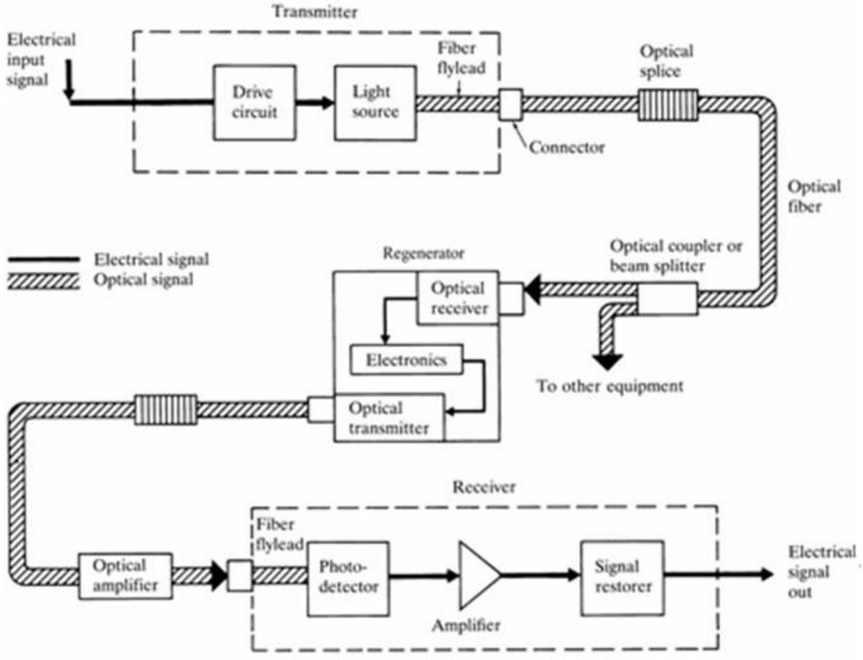
i) Bit rate: 40 - 160 Gb/s
ii) Repeater spacing: 24000 km - 35000 km
iii) Operating wavelength: 1.53 to 1.57 μm

Need of fiber optic communication

i) Fiber optic communication system has emerged as most important communication
ii) system. Compared to traditional system because of following requirements:
iii) 1. In long haul transmission system there is need of low loss transmission medium
iv) 2. There is need of compact and least weight transmitters and receivers.
v) 3. There is need of increase dspan of transmission.
vi) 4. There is need of increased bit rate-distrance product.
vii) A fiber optic communication system fulfills these requirements, hence most widely
viii) accepted

Element of an Optical Fiber Transmission link

An optical fiber communication system is similar in basic concept to any type of communication system. A block schematic of a general communication system is shown in Figure.



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

1. Transmitter
2. Information channel
3. Receiver.

The basic components are light signal transmitter, the optical fiber, and the photo detecting receiver. The additional elements such as fiber and cable splicers and connectors, regenerators, beam splitters, and optical amplifiers are employed to improve the performance of the communication system.

1. Transmitter

Transmitter 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.

2. 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 waves 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.

3. Receiver

The information being transmitted is detector. In the fiber system the optic wave is converted into an electric current by a photo detector. The current developed by the detector is proportional to the power in the incident optic wave. Detector output current contains the transmitted information. This detector output is then filtered to remove the constant bias and then amplified. The important properties of photo detectors are small size, economy, long life, low power consumption, high sensitivity to optic signals and fast response to quick variations in the optic power.

Signal processing includes filtering, amplification. Proper filtering maximizes the ratio of signal to unwanted power. For a digital system decision circuit is an additional block. The bit error rate (BER) should be very small for quality communications.

The electrical forms of the message emerging from the signal processor are transformed into a sound wave or visual image. Sometimes these signals are directly usable when computers or other machines are connected through a fiber system.

Functional Advantages

The functional advantages of optical fibers are −

- The transmission bandwidth of the fiber optic cables is higher than the metal cables.
- The amount of data transmission is higher in fiber optic cables.
- The power loss is very low and hence helpful in long-distance transmissions.
- Fiber optic cables provide high security and cannot be tapped.
- Fiber optic cables are the most secure way for data transmission.
- Fiber optic cables are immune to electromagnetic interference.
- These are not affected by electrical noise.

Physical Advantages

The physical advantages of fiber optic cables are −

- The capacity of these cables is much higher than copper wire cables.
- Though the capacity is higher, the size of the cable doesn’t increase like it does in copper wire cabling system.
- The space occupied by these cables is much less.
- The weight of these FOC cables is much lighter than the copper ones.
- Since these cables are di-electric, no spark hazards are present.

- These cables are more corrosion resistant than copper cables, as they are bent easily and are flexible.
- The raw material for the manufacture of fiber optic cables is glass, which is cheaper than copper.
- Fiber optic cables last longer than copper cables.

Disadvantages

Although fiber optics offer many advantages, they have the following drawbacks −

- Though fiber optic cables last longer, the installation cost is high.
- The number of repeaters are to be increased with distance.
- They are fragile if not enclosed in a plastic sheath. Hence, more protection is needed than copper ones.

Applications of Fiber Optics

The optical fibers have many applications. Some of them are as follows −

- Used in telephone systems
- Used in sub-marine cable networks
- Used in data link for computer networks, CATV Systems
- Used in CCTV surveillance cameras
- Used for connecting fire, police, and other emergency services.
- Used in hospitals, schools, and traffic management systems.
- They have many industrial uses and also used for in heavy duty constructions.

Optical Fiber Waveguides

In free space light travels as its maximum possible speed i.e. 3 x 108 m/s or 186 x 103 miles/sec. When light travels through a material it exhibits certain behavior explained by laws of eflection, refraction.

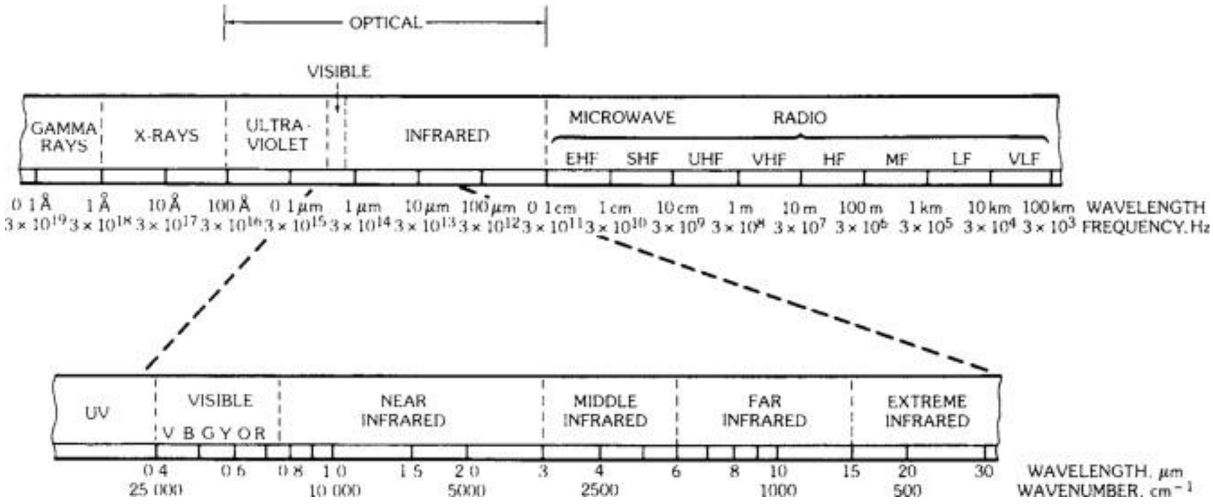
a. Electromagnetic Spectrum

The radio waves and light are electromagnetic waves. The rate at which they alternate in polarity is called their frequency (f) measured in hertz (Hz). The speed of electromagnetic wave (c) in free space is approximately 3 x 108 m/sec. The distance travelled during each cycle is called as wavelength (λ)

$$wavelength\ (\lambda) = \frac{speed\ of\ light}{freuency} = \frac{c}{f}$$

In fiber optics, it is more convenient to use the wavelength of light instead of the frequency with light frequencies, wavlengfth is often stated in microns or nanometres 1 micron (μ) = 1 Micrometre (1 x 10-6)1 nano (n) = 10-9 metre

Fig. shows electromagnetic frequency spectrum.



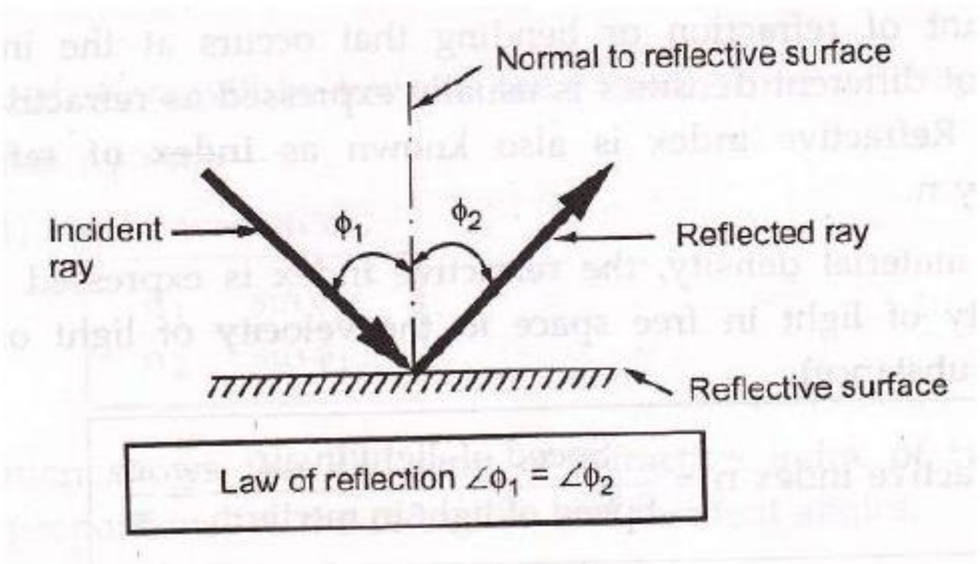
Fiber optics uses visible and infrared light. Infrared light covers a fairly wide range of wavelengths and is generally used for all fiber optic communications. Visible light is normally used for very short-range transmission using a plastic fiber.

Ray Transmission Theory

Before studying how the light actually propagates through the fiber, laws governing the nature of light m ust be studied. These was 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 x 108 m/s or 186 x 103 miles/sec. When light travels through a material it exhibits certain behavior 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 1 from imaginary perpendicular normal, the ray will be reflected from the surface at some angle 2 from normal which is equal to the angle of incidence. Fig. shows law of reflection.

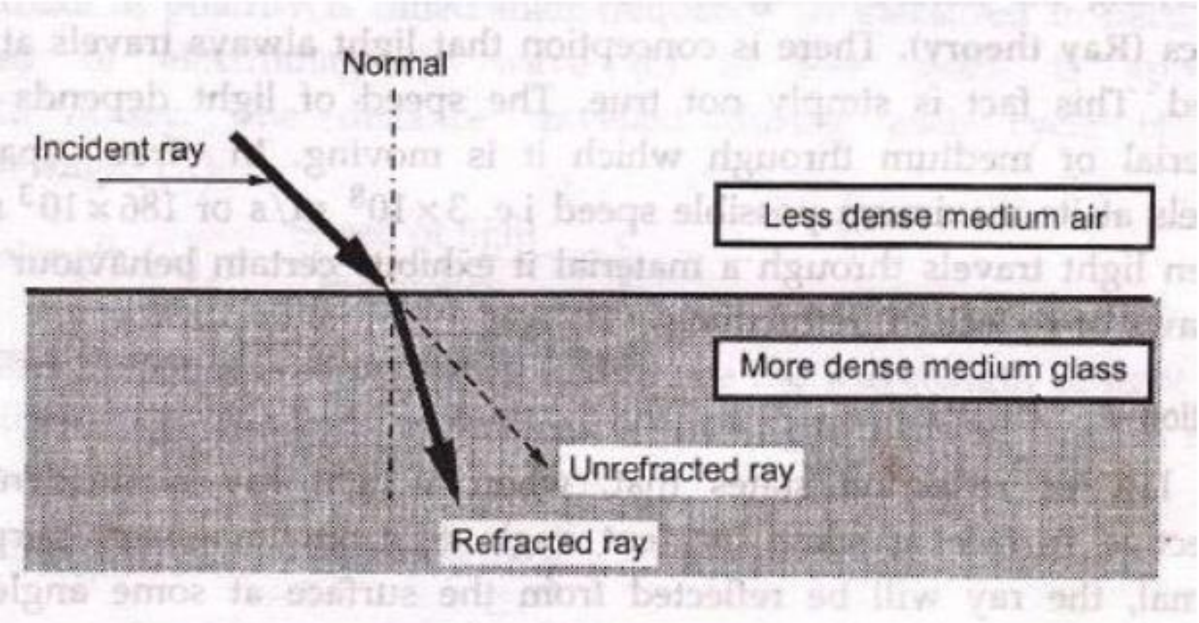


Refraction

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. 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.



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).

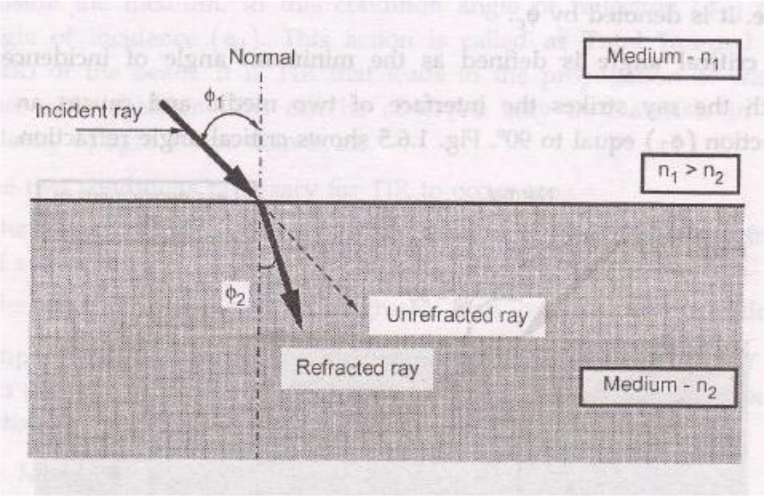
- $Refractive\ index\ n = \frac{speed\ of\ light\ in\ air}{speed\ of\ light\ in\ medium} = \frac{c}{v}$
- The refractive index for vacuum and air os 1.0 for water it is 1.3 and for glass refractive index is 1.5.

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.
- □1 and □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,

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

- A refractive index model for Snell‘s law is shown in Fig.

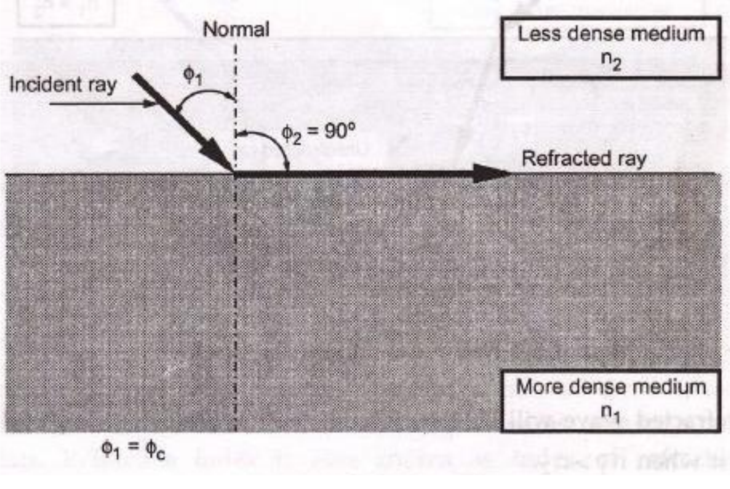


- The refracted wave will be towards the normal when n1 < n2 and will away from it then n1 > n2.
- Equation can be written as,

$$\frac{n_1}{n_2} = \frac{sin\emptyset_2}{sin\emptyset_1}$$

Critical Angle

- When the angle of incidence (□1) is progressively increased, there will be progressive increase of refractive angle (□ 2). At some condition (□ 1) the refractive angle (□2) becomes 90o to the normal.
- When this happens the refracted light ray travels along the interface. The angle of incidence (□1) at the point at which the refractive angle (□ 1) becomes 90 degree is called the critical angle. It is denoted by □c.
- The critical angle is defined as the minimum angle of incidence (□1) at which the ray strikes the interface of two media and causes an angle of refraction (2) equal to 90o. Fig shows critical angle refraction
- Hence at critical angle 1 = c and 2 = 90o .Using Snell‘s law: n1 sin 1 = n2 sin 2



$$\sin\phi_c = \frac{n_2}{n_1}\sin 90^\circ$$

$$\sin 90^\circ = 1$$

$$\sin\phi_c = \frac{n_2}{n_1}$$

$$\text{Critical angle } \phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

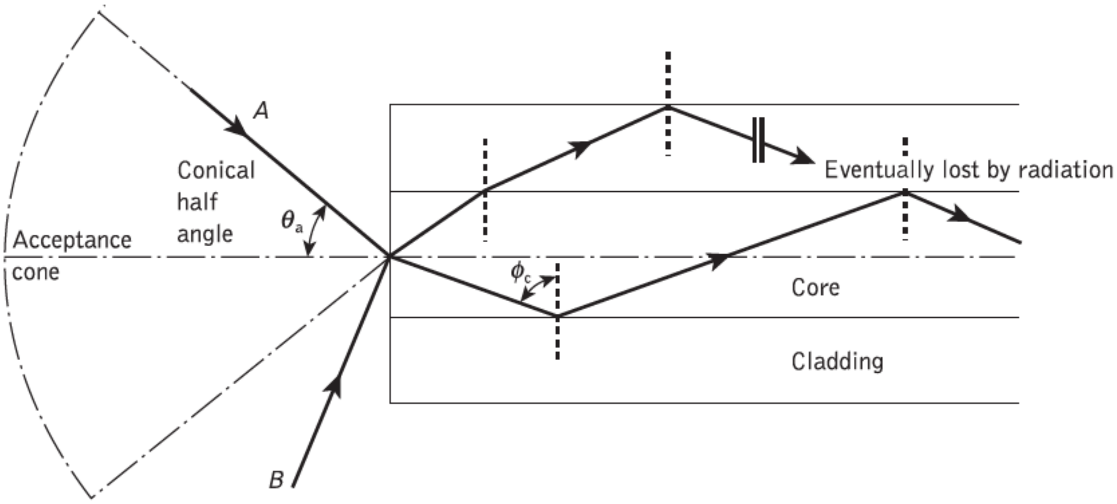
The actual value of critical angle is dependent upon combination of materials present on each side of boundary.

Total Internal Reflection (TIR)

- When the incident angle is increase 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 (□ 2) is equal to angle of incidence (□1). This action is called as Total Internal Reflection (TIR) of the beam. It is TIR that leads to the propagation of waves within fiber-cable medium. TIR can be observed only in materials in which the velocity of light is less than in air.
- The two conditions necessary for TIR to occur are:
  1. The refractive index of first medium must be greater than the refractive index of second one.
  2. The angle of incidence must be greater than (or equal to) the critical angle.

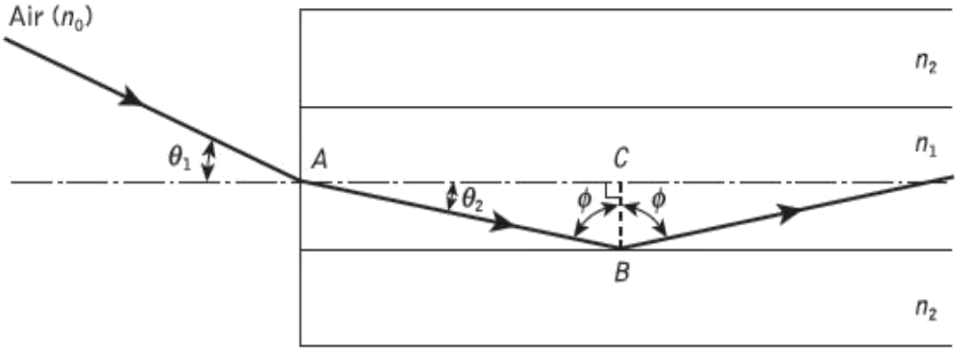
Acceptance Angle

- **Acceptance angle is the maximum angle with the axis of the Optical Fiber at which the light can enter into the optical fiber in order to be propagated through it.**



Applying Snell‘s law to external incidence angle.

$$n_0 sin\theta_a = n_1 sin\theta_2 \qquad ……..(1)$$



$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_1}{n_0} \qquad \text{or} \qquad \sin\theta_i = \frac{n_1}{n_0}\sin\theta_r \tag{1}$$

But in right angled triangle OBL, $\sin\theta_r = \sin(90^\circ - \emptyset) = \cos\emptyset$

$$\therefore \qquad \sin\theta_i = \frac{n_1}{n_0}\cos\emptyset \tag{2}$$

When $\phi = \phi_c$ then $\theta_i = \theta_{max}$

$$\text{Thus,} \qquad \sin\theta_{max} = \frac{n_1}{n_0}\cos\emptyset_c \tag{3}$$

Now, applying Snell's law at core-cladding interface,

$$\frac{\sin\emptyset_c}{\sin 90^\circ} = \frac{n_2}{n_1} \qquad \text{or} \qquad \sin\emptyset_c = \frac{n_2}{n_1}$$

$$\text{or} \qquad \sqrt{(1 - \cos^2\emptyset_c)} = \frac{n_2}{n_1}$$

$$\text{or} \qquad 1 - \cos^2\emptyset_c = \frac{{n_2}^2}{{n_1}^2}$$

$$\therefore \qquad \cos\emptyset_c = \frac{\sqrt{{n_1}^2 - {n_2}^2}}{n_1} \tag{4}$$

$$\text{Hence,} \qquad \sin\theta_{max} = \frac{\sqrt{{n_1}^2 - {n_2}^2}}{n_0} \tag{5}$$

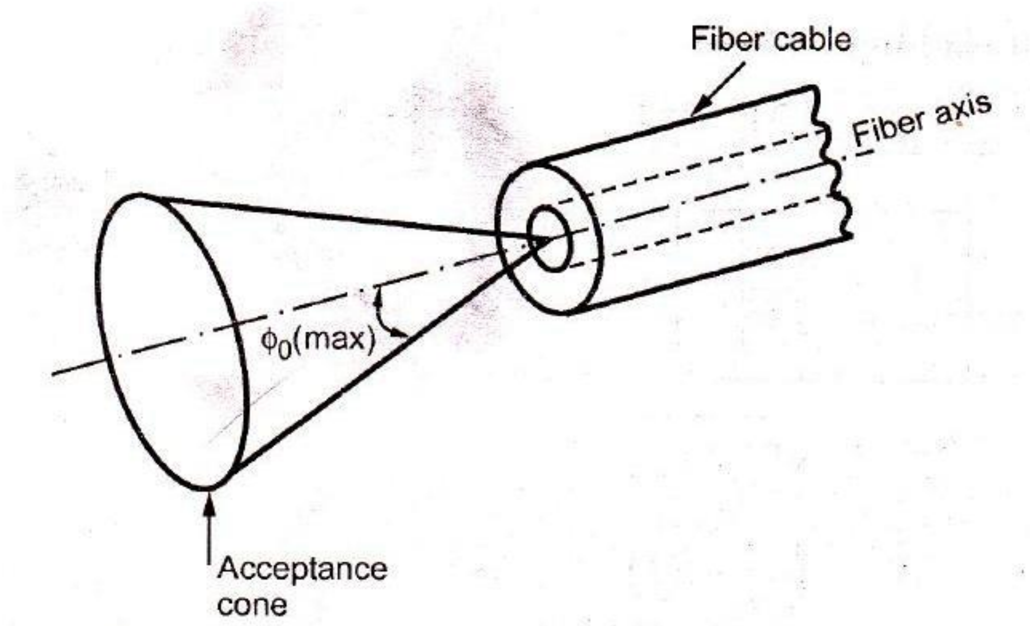
Therefore acceptance angle

$$\theta_{max} = \sin^{-1}\frac{\sqrt{{n_1}^2 - {n_2}^2}}{n_0}$$

For air $n_0 = 1$

$$\boxed{\theta_{max} = \sin^{-1}\sqrt{{n_1}^2 - {n_2}^2}} \tag{6}$$

This is the expression for the acceptance angle. The light rays contained within the cone having a full angle $2\theta_{max}$ are accepted into the core of the fibre for propagation. Such a cone is therefore known as ***acceptance cone***.



The Cone of acceptance is the angle within which the light is accepted into the core and is able to travel along the fiber. The launching of light wave becomes easier for large acceptance cone. The angle is measured from the axis of the positive cone so the total angle of convergence is actually twice the stated value.

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.

$$NA = \sin\theta_{max} = \frac{\sqrt{{n_1}^2-{n_2}^2}}{n_0} \tag{8}$$

For air $n_0 = 1$

$$\therefore \quad NA = \sin\theta_{max} = \sqrt{{n_1}^2-{n_2}^2} \tag{9}$$

Now, $${n_1}^2-{n_2}^2 = (n_1+n_2)(n_1-n_2) = \frac{(n_1+n_2)}{2}\frac{(n_1-n_2)}{n_1}2n_1$$

We can take approximately $\frac{(n_1+n_2)}{2} \approx n_1$ and since $\Delta = \frac{(n_1-n_2)}{n_1}$

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

Or $$\boxed{NA = \sqrt{{n_1}^2-{n_2}^2} = n_1\sqrt{2\Delta}} \tag{10}$$

The values of NA typically range from about 0.1 to 0.5.

Skew Rays: Skew rays are the rays which does not follow the fiber axis. These rays are not easy to visualize, only the direction can be predicted in helical path of direction change of 2γ at each reflection. γ is the angle between the projection of the ray in the two dimension and the radii of the fiber core at the point of reflection. When the light input to the fiber is non uniform, rays will therefore tend to have a smoothing effect on the distribution of light as it is transmitted, giving more information output. NA in case of skew rays,

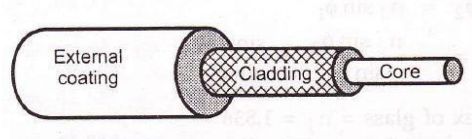
$$\boxed{NA = \eta_0 \sin \theta as \cos \gamma = (\eta_1^2 - \eta_2^2)^{1/2}}$$

Optical Fiver as Waveguide

An optical fiber is a cylindrical dielectric waveguide capable of conveying electromagnetic waves at optical frequencies. The electromagnetic energy is in the form of the light and propagates along the axis of the fiber. The structural of the fiver determines the transmission characteristics.

The propagation of light along the waveguide is decided by the modes of the waveguides, here mode means path. Each mode has distict pattern of electric and magnetic field distributions along the fiber length. Only few modes can satisfy the homogeneous wave equation in the fiver also the boundary condition a waveguide surfaces. When there is only one path for light to follow then it is called as single mode propagation. When there is more than one path then it is called as multimode propagation. Single fiber structure.

A single fiber structure is shown in Fig. It consists of a solid dielectric cylinder with radius _a ‘. This cylinder is called as core of fiber. The core is surrounded by dielectric, called cladding. The index of refraction of core (glass fiber) is slightly greater than the index of refraction of cladding. If refractive index of core (glass fiver) = n1 and refractive index of cladding = n2 then n1 > n2.



Modes of Fiber

Fiber cables cal 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.

1. Single mode fiber
2. 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 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.

Fiber Profiles

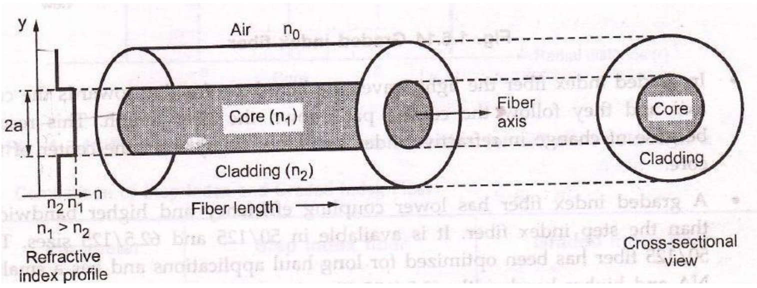
- A fiber is characterized by its profile and by its core and cladding diameters.
- One way of classifying the fiber cables is according to the index profile at fiber. The index profile is a graphical representation of value of refractive index across the core diameter.

There are two basic types of index profiles.

1. Step index fiber.
2. Graded index fiber.

Step Index (SI) Fiber

The step index (SI) fiber is a cylindrical waveguide core with central or inner core has a uniform refractive index of n1 and the core is surrounded by outer cladding with uniform refractive index of n2. The cladding refractive index (n2) is less than the core refractive index
(n1). But there is an abrupt change in the refractive index at the core cladding interface. Refractive index profile of step indexed optical fiber is shown in Fig. The refractive index is plotted on horizontal axis and radial distance from the core is plotted on vertical axis.



The propagation of light wave within the core of step index fiber takes the path of meridional ray i.e. ray follows a zig-zag path of straight line segments. The core typically has diameter of 50-80 μm and the cladding has a diameter of 125 μm.

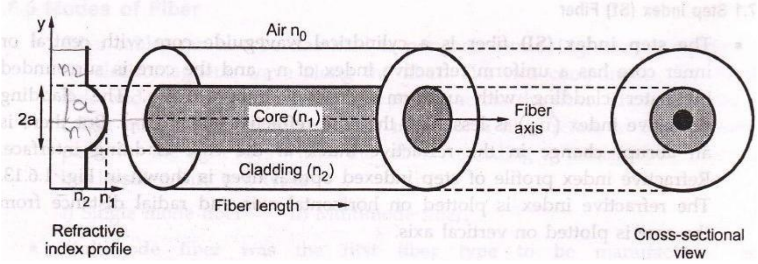
The refractive index profile is defined as –

$$n(r) = \begin{cases} n_1 & \text{when } r < a \text{ (core)} \\ n_2 & \text{when } r \geq a \text{ (cladding)} \end{cases}$$

Graded Index (GRIN) Fiber

The graded index fiber has a core made from many layers of glass.

In the graded index (GRIN) fiber the refractive index is not uniform within the core, it is highest at the center and decreases smoothly and continuously with distance towards the cladding. The refractive index profile across the core takes the parabolic nature. Fig. shows refractive index profile of graded index fiber .



In graded index fiber the light waves are bent by refraction towards the core axis and they follow the curved path down the fiber length. This results because of change in refractive index as moved away from the center of the core.

A graded index fiber has lower coupling efficiency and higher bandwidth than the step index fiber. It is available in 50/125 and 62.5/125 sizes. The 50/125 fiber has been optimized for long haul applications and has a smaller NA and higher bandwidth. 62.5/125 fiber is optimized for LAN applications which is costing 25% more than the 50/125 fiber cable.

The refractive index variation in the core is giver by relationship

$$n(r) = \begin{cases} n_1\left(1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}\right) & \text{when } r < a \ (core) \\ n_1(1 - 2\Delta)^{\frac{1}{2}} \approx n_2 & when\ r \geq a \ (\text{cladding}) \end{cases}$$

Where,
r = Radial distance from fiber axis
a = Core radius
n1 = Refractive index of core
n2 = Refractive index of cladding
α = Shape of index profile.

Comparison of Step Index and Graded Index Fiber

Sr. No.	**Parameter**	**Step index fiber**	**Graded index fiber**
1.	Data rate	Slow.	Higher
2.	Coupling efficiency	Coupling efficiency with fiber is higher.	Lower coupling efficiency.
3.	Ray path	By total internal reflection.	Light ray travels in oscillatory fashion.
4.	Index variation	$\Delta = \frac{n_1 - n_2}{n_1}$	$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$
5.	Numerical aperture	NA remains same.	Changes continuously with distance from fiber axis.
6.	Material used	Normally plastic or glass is preferred.	Only glass is preferred.
7.	Bandwidth efficiency	10 – 20 MHz/km	1 GHz/km
8.	Pulse spreading	Pulse spreading by fiber length is more.	Pulse spreading is less
9.	Attenuation of light	Less typically 0.34 dB/km at	More 0.6 to 1 dB/km at 1.3

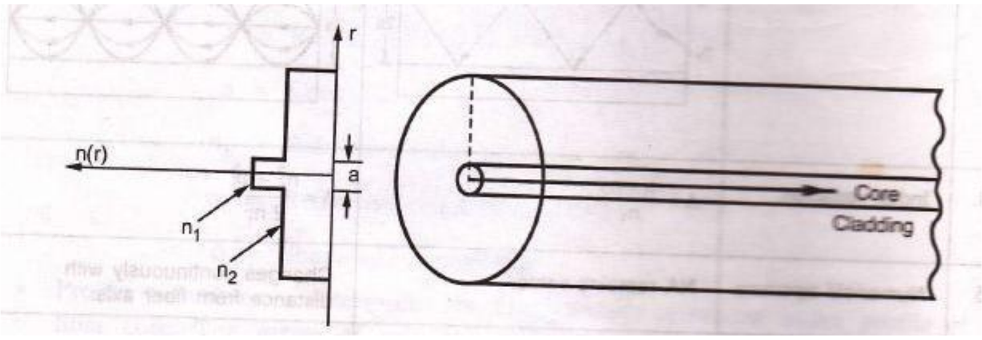
Optic Fiber Configurations

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 -

- Single mode step index fiber.
- Multimode step index fiber.
- 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 mono mode fiber. Fig. shows single mode fiber.



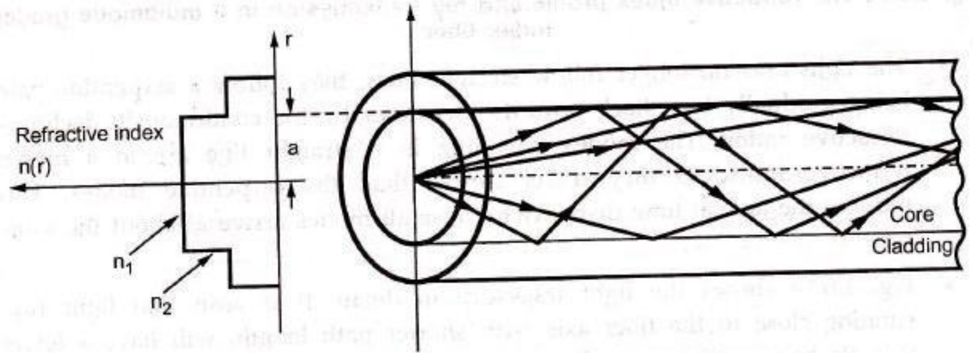
Single mode fiber will permit only one mode to propagate and does not suffer from mode delay differences. These are primarily developed for the 1300 nm window but they can be also be used effectively with time division multiple (TDM) and wavelength division multiplex (WDM) systems operating in 1550 nm 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 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 paths that a light ray may follow during the propagation.

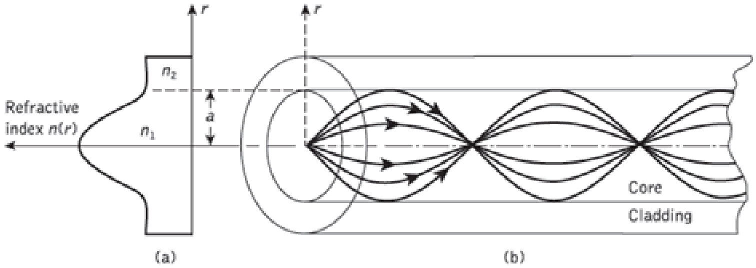
The light ray is propagated using the principle of total internal reflection (TIR). Since the core index of refraction is higher than the cladding index of refraction, the light enters at less than critical angle is guided along the fiber.



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.

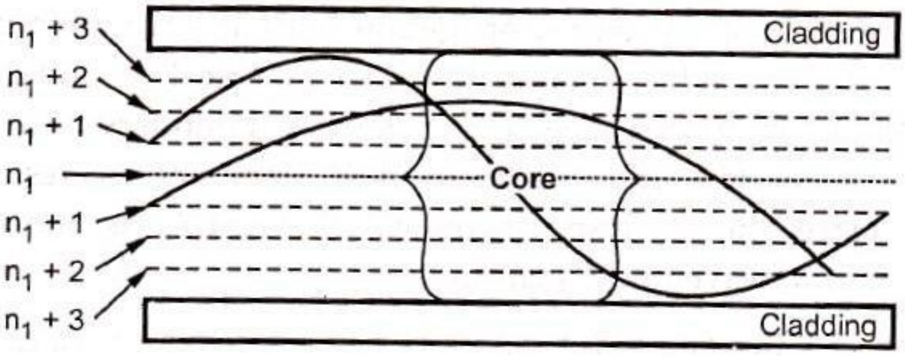
Multimode Graded Index Fiber

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 denser medium. Therefore, the light rays are being constantly being refracted and ray is bending continuously. This cable is mostly used for long distance communication. Fig shows multimode graded index fiber.



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. shows the light trajectory in detail. It is seen that light rays running close to the fiber axis with shorter path length, will have a lower velocity because they pass through a region with a high refractive index.



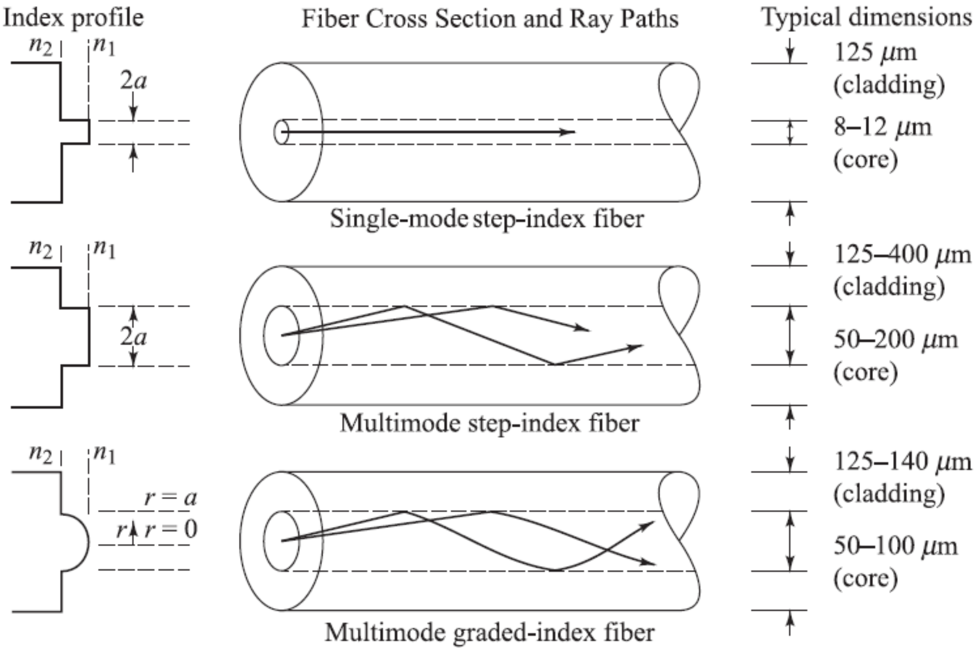
Rays on core edges offers reduced refractive index, hence travel more faster than axial rays and cause the light components to take same amount of time to travel the length of fiber, thus, minimizing dispersion losses. Each path at a different angle is termed as ‘transmission mode’ and the NA of graded index fiber is defined as the maximum value of acceptance angle at the fiber axis.

Typical attenuation coefficients of graded index fibers at 850 nm are 2.5 to 3 dB/km, while at 1300 nm they are 1.0 to 1.5 dB/km.

The main advantages of graded index fiber are:

1. Reduced refractive index at the centre of core.
2. Comparatively cheap to produce.

Comparison of single mode and multimode fiber:



Comparison of conventional single-mode and multimode step-index and graded-index optical fibers

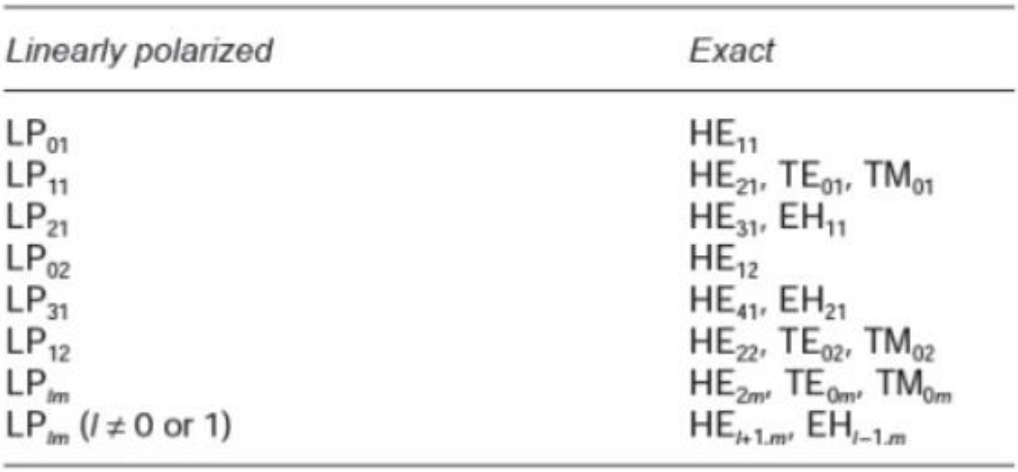
Mode Theory for Cylindrical Waveguide

To analyse the optical fiber propagation mechanism within a fiber, Maxwell equations are to solve subject to the cylindrical boundary conditions at core-cladding interface. The core-cladding boundary conditions lead to coupling of electric and magnetic field components resulting in hybrid modes. Hence the analysis of optical waveguide is more complex than metallic hollow waveguide analysis.

Depending on the large E-field, the hybrid modes are HE or EH modes. The two lowest order does are HE11 and TE01.

Linearly Polarized Mode:

- The exact solution of Maxwell's equations for a cylindrical homogeneous core dielectric waveguide involves much algebra and yields a complex result.
- In common with the planar guide, TE (where $E_z = 0$) and TM (where $H_z = 0$) modes are obtained within the dielectric cylinder.
- The cylindrical waveguide, however, is bounded in two dimensions rather than one. Thus two integers, *l* and *m*, are necessary in order to specify the modes, in contrast to the single integer (*m*) required for the planar guide.
- For the cylindrical waveguide we therefore refer to TE*lm* and TM*lm* modes.
- These modes correspond to meridional rays traveling within the fiber.
- However, hybrid modes where E_z and H_z are nonzero also occur within the cylindrical waveguide.
- These modes, which result from skew ray propagation within the fiber, are designated HE*lm* and EH*lm* depending upon whether the components of **H** or **E** make the larger contribution to the transverse (to the fiber axis) field.
- Thus an exact description of the modal fields in a step index fiber proves somewhat complicated.
- The relationship between the traditional HE, EH, TE and TM mode designations and the LP*lm* mode designations is shown in Table



Linearly polarized	*Exact*
LP_{01}	HE_{11}
LP_{11}	HE_{21}, TE_{01}, TM_{01}
LP_{21}	HE_{31}, EH_{11}
LP_{02}	HE_{12}
LP_{31}	HE_{41}, EH_{21}
LP_{12}	HE_{22}, TE_{02}, TM_{02}
LP_{lm}	HE_{2m}, TE_{0m}, TM_{0m}
LP_{lm} ($l \neq 0$ or 1)	$HE_{l+1,m}$, $EH_{l-1,m}$

Summary of Key Modal Concepts

Normalized frequency variable, V is defined as

$$V = \frac{2\pi a(n_1^2 - n_2^2)^{1/2}}{\lambda}$$

Where, a = Core radius

λ = Free space wavelength

$$V = \frac{2\pi a}{\lambda} NA$$

Since $(n_1^2 - n_2^2)^{1/2} = NA$

The total number of modes in a multimode fiber is given by

$$M = \frac{1}{2}\left(\frac{2\pi a}{\lambda}\right)^2 (n_1^2 - n_2^2)$$

$$M = \frac{1}{2}\left[\frac{2\pi a}{\lambda} NA\right]^2 = \frac{[V]^2}{2}$$

$$M = \frac{1}{2}\left[\frac{\pi d}{\lambda}.NA\right]^2$$

Example 1: Calculate the number of modes of an optical fiber having diameter of 50 µm, n1 = 1.48, n2 = 1.46 and λ = 0.82 µm.

Solution: d = 50 µm

n1 = 1.48

n2 = 1.46

λ = 0.82 µm

$$NA = (n_1^2 - n_2^2)^{1/2}$$

Number of modes is given by,

$$M = \frac{1}{2}\left[\frac{\pi d}{\lambda}.NA\right]^2$$

$$M = \frac{1}{2}\left[\frac{\pi (50 X 10^{-6})}{0.82 X 10^{-6}} X 0.243\right]^2$$

UNIT-II SIGNAL DEGRADATION OPTICAL FIBERS

- Attenuation
- Absorption losses
- scattering losses
- Bending Losses
- Core and Cladding losses
- Signal Distortion in Optical Waveguides
- Information Capacity determination
- Group Delay
- Material Dispersion
- Wave guide Dispersion,
- Signal distortion in SM fibers
- Polarization Mode dispersion
- Intermodal dispersion
- Pulse Broadening in GI fibers
- Mode Coupling
- Design Optimization of SM fibers
- RI profile and cut-off wavelength.

Attenuation

The attenuation or transmission loss of optical fibers has proved to be one of the most important factors in bringing about their wide acceptance in telecommunications. As channel attenuation largely determined the maximum transmission distance prior to signal restoration, optical fiber communications became especially attractive when the transmission losses of fibers were reduced below those of the competing metallic conductors (less than 5 dB km−1).

Signal attenuation within optical fibers, as with metallic conductors, is usually expressed in the logarithmic unit of the decibel. The decibel, which is used for comparing two power levels, may be defined for a particular optical wavelength as the ratio of the input (transmitted) optical power P_i into a fiber to the output (received) optical power P_o from the fiber as:

$$\text{Number of decibels (dB)} = 10 \log_{10} \frac{P_i}{P_o} \tag{2.1}$$

This logarithmic unit has the advantage that the operations of multiplication and division reduce to addition and subtraction, while powers and roots reduce to multiplication and division. However, addition and subtraction require a conversion to numerical values which may be obtained using the relationship:

$$\frac{P_i}{P_o} = 10^{(\mathrm{dB}/10)} \tag{2.2}$$

In optical fiber communications the attenuation is usually expressed in decibels per unit length (i.e. dB km−1) following:

$$\alpha_{\mathrm{dB}} L = 10 \log_{10} \frac{P_i}{P_o} \tag{2.3}$$

where α_{dB} is the signal attenuation per unit length in decibels which is also referred to as the fiber loss parameter and L is the fiber length. A number of mechanisms are responsible for the signal attenuation within optical fibers. These mechanisms are influenced by the material composition, the preparation and purification technique, and the waveguide structure. They may be categorized within several major areas which include material absorption, material scattering (linear and nonlinear scattering), curve and microbending losses, mode coupling radiation losses and losses due to leaky modes.

Material absorption losses in silica glass fibers

Material absorption is a loss mechanism related to the material composition and the fabrication process for the fiber, which results in the dissipation of some of the transmitted optical power as heat in the waveguide. The absorption of the light may be intrinsic (caused by the interaction with one or more of the major components of the glass) or extrinsic (caused by impurities within the glass).

Intrinsic absorption

An absolutely pure silicate glass has little intrinsic absorption due to its basic material structure in the near-infrared region. However, it does have two major intrinsic absorption mechanisms at optical wavelengths which leave a low intrinsic absorption window over the 0.8 to 1.7 µm wavelength range, as illustrated in Figure 2.1, which shows a possible optical attenuation against wavelength characteristic for absolutely pure glass.

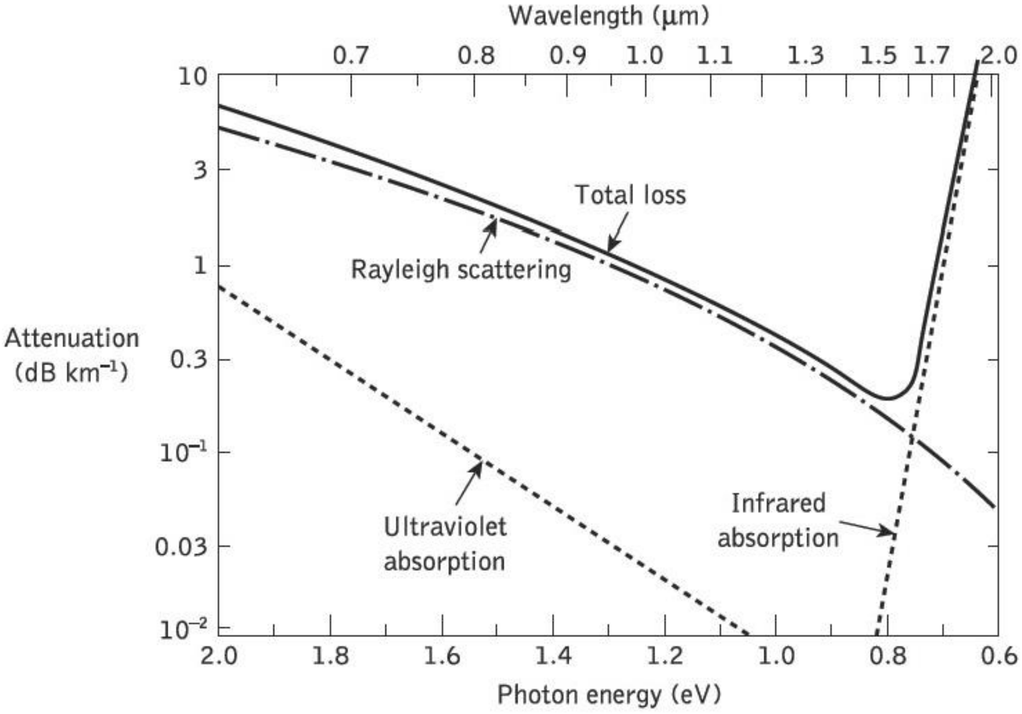


Figure 2.1 The attenuation spectra for the intrinsic loss mechanisms in pure GeO2–SiO2 glass

It may be observed that there is a fundamental absorption edge, the peaks of which are centered in the ultraviolet wavelength region. This is due to the stimulation of electron transitions within the glass by higher energy excitations.

The tail of this peak may extend into the window region at the shorter wavelengths, as illustrated in Figure 2.1. Also in the infrared and far infrared, normally at wavelengths above 7 µm, fundamentals of absorption bands from the interaction of photons with molecular vibrations within the glass occur.

These give absorption peaks which again extend into the window region. The strong absorption bands occur due to oscillations of structural units such as Si–O (9.2 µm), P–O (8.1 µm), B–O (7.2 µm) and Ge–O (11.0µm) within the glass. Hence, above 1.5 µm the tails of these largely far-infrared absorption peaks tend to cause most of the pure glass losses.

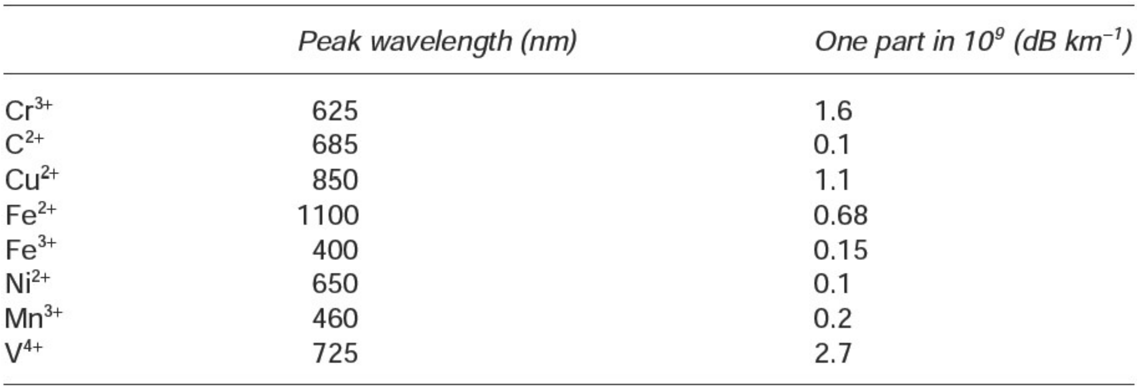
However, the effects of both these processes may be minimized by suitable choice of both core and cladding compositions. For instance, in some non oxide glasses such as fluorides and chlorides, the infrared absorption peaks occur at much longer wavelengths which are well into the far infrared (up to 50 µm), giving less attenuation to longer wavelength transmission compared with oxide glasses.

Extrinsic absorption

In practical optical fibers prepared by conventional melting techniques, a major source of signal attenuation is extrinsic absorption from transition metal element impurities.

Some of the more common metallic impurities found in glasses are shown in the Table 2.1, together with the absorption losses caused by one part in 109

Table 2.1 Absorption losses caused by some of the more common metallic ionimpurities in glasses, together with the absorption peak wavelength



	Peak wavelength (nm)	*One part in 10^9 (dB km^{-1})*
Cr^{3+}	625	1.6
C^{2+}	685	0.1
Cu^{2+}	850	1.1
Fe^{2+}	1100	0.68
Fe^{3+}	400	0.15
Ni^{2+}	650	0.1
Mn^{3+}	460	0.2
V^{4+}	725	2.7

It may be noted that certain of these impurities, namely chromium and copper, in their worst valence state can cause attenuation in excess of 1 dB km−1 in the near-infrared region. Transition element contamination may be reduced to acceptable levels (i.e. one part in 1010) by glass refining techniques such as vapor-phase oxidation, which largely eliminates the effects of these metallic impurities.

However, another major extrinsic loss mechanism is caused by absorption due to water (as the hydroxyl or OH ion) dissolved in the glass. These hydroxyl groups are bonded into the glass structure and have fundamental stretching vibrations which occur at wavelengths between 2.7 and 4.2μm depending on group position in the glass network. The fundamental vibrations give rise to overtones appearing almost harmonically at 1.38, 0.95 and 0.72 μm, as illustrated in Figure 2.2. This shows the absorption spectrum for the hydroxyl group in silica.

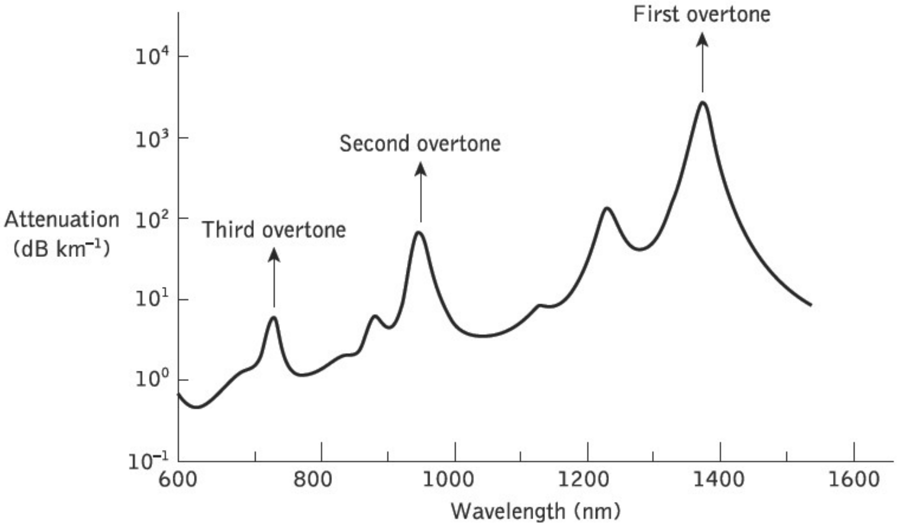


Figure 2.2 The absorption spectrum for the hydroxyl (OH) group in silica.

Furthermore, combinations between the overtones and the fundamental SiO2 vibration occur at 1.24, 1.13 and 0.88 μm, completing the absorption spectrum shown in Figure 2.2.It may also be observed in Figure 3.2 that the only significant absorption band in the region below a wavelength of 1 μm is the second overtone at 0.95 μm which causes attenuation of about 1 dB km−1 for one part per million (ppm) of hydroxyl.

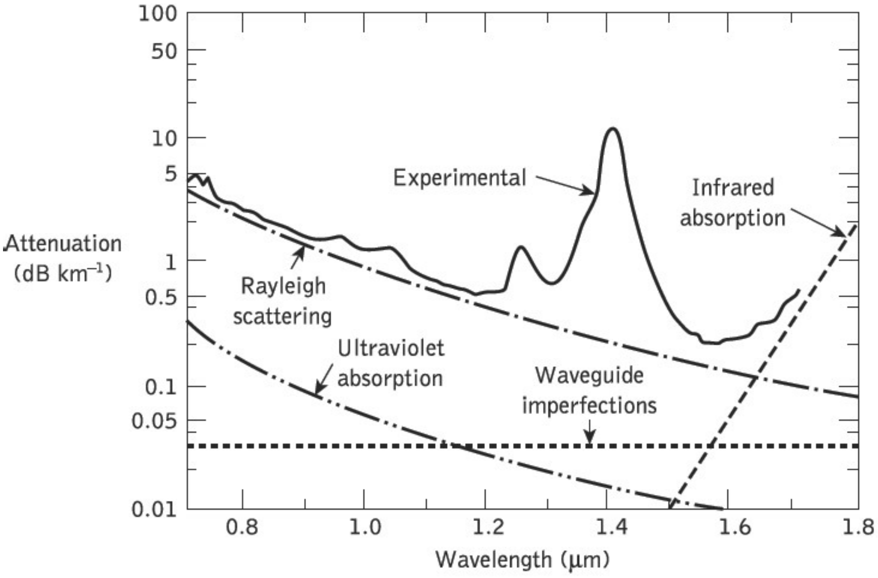


Figure 2.3 The measured attenuation spectrum for an ultra-low-loss single-mode fiber (solid line) with the calculated attenuation spectra for some of the loss mechanisms contributing to the overall fiber attenuation

At longer wavelengths the first overtone at 1.383 μm and its sideband at 1.24 μm are strong absorbers giving attenuation of about 2 dB km−1 ppm and 4 dB km−1 ppm respectively. Since most resonances are sharply peaked, narrow windows exist in the longer wavelength region around 1.31 and 1.55 μm which are essentially unaffected by OH absorption once the impurity level has been reduced below one part in 107. This situation is illustrated in Figure 2.3, which shows the attenuation spectrum of a low-loss single-mode fiber produced in 1979. It may be observed that the lowest attenuation for this fiber occurs at a wavelength of 1.55 μm and is 0.2 dB km−1. Despite this value approaching the minimum possible attenuation of around 0.18 dB km−1 at the 1.55 μm wavelength, it should be noted that the transmission loss of an ultra-low-loss pure silica core fiber was more recently measured as 0.1484 dB km−1 at the slightly longer wavelength of 1.57μm.

Although in standard, modern single-mode fibers the loss caused by the primary OH peak at 1.383 μm has been reduced below 1 dB km−1, it still limits operation over significant distances to

the lower loss windows at 1.31 and 1.55 μm.

Linear scattering losses

Linear scattering mechanisms cause the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly (proportionally to the mode power) into a different mode. This process tends to result in attenuation of the transmitted light as the transfer may be to a leaky or radiation mode which does not continue to propagate within the fiber core, but is radiated from the fiber. It must be noted that as with all linear processes, there is no change of frequency on scattering.

Linear scattering may be categorized into two major types: Rayleigh and Mie scattering. Both result from the nonideal physical properties of the manufactured fiber which are difficult and, in certain cases, impossible to eradicate at present.

Rayleigh scattering

Rayleigh scattering is the dominant intrinsic loss mechanism in the low-absorption window between the ultraviolet and infrared absorption tails. It results from inhomogeneities of a random nature occurring on a small scale compared with the wavelength of the light.

These inhomogeneities manifest themselves as refractive index fluctuations and arise from density and compositional variations which are frozen into the glass lattice on cooling. The compositional variations may be reduced by improved fabrication, but the index fluctuations caused by the freezing-in of density inhomogeneities are fundamental and cannot be avoided.

The subsequent scattering due to the density fluctuations, which is in almost all directions, produces an attenuation proportional to $1/\lambda4$ following the Rayleigh scattering formula. For a single-component glass this is given by:

$$\gamma_{\mathrm{R}} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_{\mathrm{c}} K T_{\mathrm{F}} \tag{2.4}$$

where γR is the Rayleigh scattering coefficient, λ is the optical wavelength, n is the refractive index of the medium, p is the average photoelastic coefficient, βc is the isothermal compressibility at a fictive temperature TF, and K is Boltzmann’s constant. The fictive temperature is defined as the temperature at which the glass can reach a state of thermal equilibrium and is closely related to the anneal temperature. Furthermore, the Rayleigh scattering coefficient is related to the transmission loss factor (transmissivity) of the fiber following the relation:

$$\mathscr{L} = \exp(-\gamma_{\mathrm{R}} L) \tag{2.5}$$

where L is the length of the fiber. It is apparent from Eq. (2.4) that the fundamental component of Rayleigh scattering is strongly reduced by operating at the longest possible wavelength.

Mie scattering

Linear scattering may also occur at inhomogeneities which are comparable in size with the guided wavelength. These result from the nonperfect cylindrical structure of the waveguide and may be caused by fiber imperfections such as irregularities in the core cladding interface, core cladding refractive index differences along the fiber length, diameter fluctuations, strains and bubbles. When the scattering inhomogeneity size is greater than $\lambda/10$, the scattered intensity which has an angular dependence can be very large.

The scattering created by such inhomogeneities is mainly in the forward direction and is called Mie scattering. Depending upon the fiber material, design and manufacture, Mie scattering can cause significant losses. The inhomogeneities may be reduced by:

- ✓ removing imperfections due to the glass manufacturing process;
- ✓ carefully controlled extrusion and coating of the fiber;
- ✓ increasing the fiber guidance by increasing the relative refractive index difference.

By these means it is possible to reduce Mie scattering to insignificant levels.

Nonlinear scattering losses

Optical waveguides do not always behave as completely linear channels whose increase in output optical power is directly proportional to the input optical power. Several nonlinear effects occur, which in the case of scattering cause disproportionate attenuation, usually at high optical power levels.

This nonlinear scattering causes the optical power from one mode to be transferred in either the forward or backward direction to the same, or other modes, at a different frequency. It depends critically upon the optical power density within the fiber and hence only becomes significant above threshold power levels.

The most important types of nonlinear scattering within optical fibers are stimulated Brillouin and Raman scattering, both of which are usually only observed at high optical power densities in long single-mode fibers. These scattering mechanisms in fact give optical gain but with a shift infrequency, thus contributing to attenuation for light transmission at a specific wavelength. However,it may be noted that such nonlinear phenomena can also be used to give optical amplification in the context of integrated optical techniques

Stimulated Brillouin scattering

Stimulated Brillouin scattering (SBS) may be regarded as the modulation of light through thermal molecular vibrations within the fiber. The scattered light appears as upper and lower sidebands which are separated from the incident light by the modulation frequency. The incident photon in this scattering process produces a phonon* of acoustic frequency as well as a scattered photon. This produces an optical frequency shift which varies with the scattering angle because the frequency of the sound wave varies with acoustic wavelength.

The frequency shift is a maximum in the backward direction, reducing to zero in the forward direction, making SBS a mainly backward process. As indicated previously, Brillouin scattering is only significant above a threshold power density. Assuming that the polarization state of the transmitted light is not maintained, it may be shown that the threshold power PB is given by:

$$P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB} \nu \text{ watts} \tag{2.6}$$

where d and λ are the fiber core diameter and the operating wavelength, respectively, both measured in micrometers, αdB is the fiber attenuation in decibels per kilometer and ν is the source bandwidth (i.e. injection laser) in gigahertz. The expression given in Eq. (2.6) allows the determination of the threshold optical power which must be launched into a single-mode optical fiber before SBS occurs

Stimulated Raman scattering

Stimulated Raman scattering (SRS) is similar to SBS except that a high-frequency optical phonon rather than an acoustic phonon is generated in the scattering process. Also, SRS can occur in both the forward and backward directions in an optical fiber, and may have an optical power threshold of up to three orders of magnitude higher than the Brillouin threshold in a particular fiber.

Using the same criteria as those specified for the Brillouin scattering threshold given in Eq. (2.6), it may be shown that the threshold optical power for SRS PR in a long single-mode fiber is given by:

$$P_R = 5.9 \times 10^{-2} d^2 \lambda \alpha_{dB} \text{ watts} \tag{2.7}$$

Fiber bend loss

Optical fibers suffer radiation losses at bends or curves on their paths. This is due to the energy in the evanescent field at the bend exceeding the velocity of light in the cladding and hence the guidance mechanism is inhibited, which causes light energy to be radiated from the fiber. An illustration of this situation is shown in Figure 2.5. The part of the mode which is on the outside of the bend is required to travel faster than that on the inside so that a wavefront perpendicular to the direction of propagation is maintained.

Hence, part of the mode in the cladding needs to travel faster than the velocity of light in that medium. As this is not possible, the energy associated with this part of the mode is lost through radiation. The loss can generally be represented by a radiation attenuation coefficient which has the form:

$$\alpha_r = c_1 \exp(-c_2 R)$$

where *R* is the radius of curvature of the fiber bend and *c*1, *c*2 are constants which are independent of *R*. Furthermore, large bending losses tend to occur in multimode fibers at a critical radius of curvature *R*c which may be estimated from:

$$R_c \simeq \frac{3n_1^2\lambda}{4\pi(n_1^2 - n_2^2)^{\frac{3}{2}}} \qquad (2.8)$$

It may be observed from the expression given in Eq. (2.8) that potential macrobending losses may be reduced by:

- ✓ designing fibers with large relative refractive index differences;
- ✓ operating at the shortest wavelength possible.

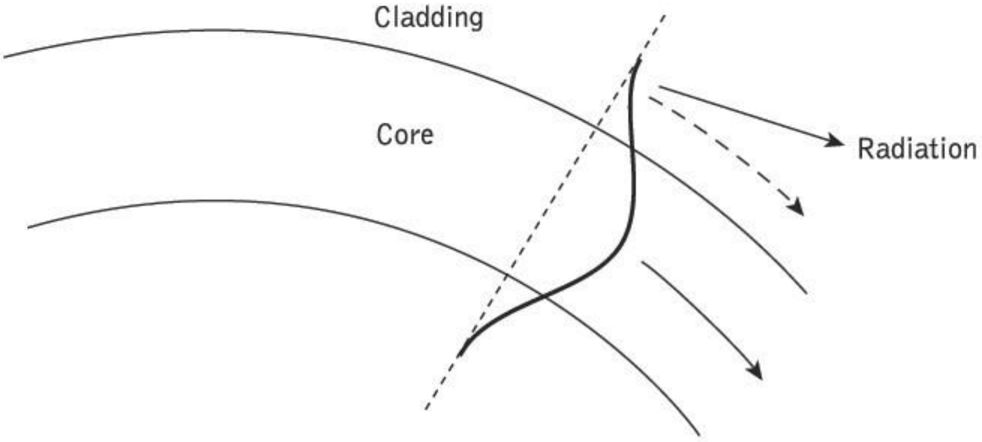


Figure 2.5 An illustration of the radiation loss at a fiber bend.

The above criteria for the reduction of bend losses also apply to single-mode fibers. One theory, based on the concept of a single quasi-guided mode, provides an expression from which the critical radius of curvature for a single-mode fiber *R*cs can be estimated as:

$$R_{cs} \simeq \frac{20\lambda}{(n_1 - n_2)^{\frac{3}{2}}}\left(2.748 - 0.996\,\frac{\lambda}{\lambda_c}\right)^{-3} \qquad (2.9)$$

where λc is the cutoff wavelength for the single-mode fiber. Hence again, for a specific single-mode fiber (i.e. a fixed relative index difference and cutoff wavelength), the critical wavelength of the radiated light becomes progressively shorter as the bend radius is decreased.

Mid-infrared and far-infrared transmission

In the near-infrared region of the optical spectrum, fundamental silica fiber attenuation is dominated by Rayleigh scattering and multiphonon absorption from the infrared absorption edge (see Figure 2.2). Therefore, the total loss decreases as the operational transmission wavelength increases until a crossover point is reached around a wavelength of 1.55 μm where the total fiber loss again increases because at longer wavelengths the loss is dominated by the phonon absorption edge. Since the near fundamental attenuation limits for near-infrared silicate class fibers have been achieved, more recently researchers have turned their attention to the mid-infrared (2 to 5 μm) and the far-infrared (8 to 12 μm) optical wavelengths.

In order to obtain lower loss fibers it is necessary to produce glasses exhibiting longer infrared cutoff wavelengths. Potentially, much lower losses can be achieved if the transmission window of the material can be extended further into the infrared by utilizing constituent atoms of higher atomic mass and if it can be drawn into fiber exhibiting suitable strength and chemical durability. The reason for this possible loss reduction is due to Rayleigh scattering which displays a λ−4 dependence and hence becomes much reduced as the wavelength is increased. For example, the scattering loss is reduced by a factor of 16 when the optical wavelength is doubled.

Thus it may be possible to obtain losses of the order of 0.01 dB km−1 at a wavelength of 2.55 μm, with even lower losses at wavelengths of between 3 and 5 μm. Candidate glass-forming systems for mid-infrared transmission are fluoride, fluoride–chloride, chalcogenide and oxide.

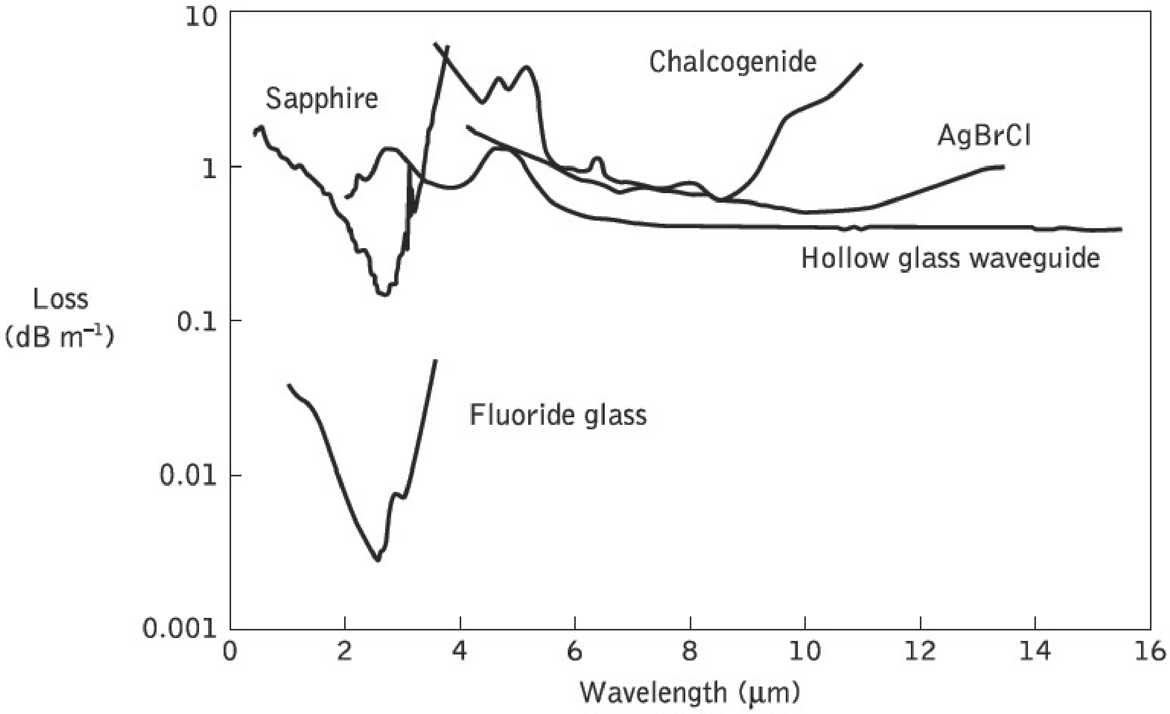


Figure 2.6 Attenuation spectra for some common mid- and far-infrared fibers

In particular, oxide glasses such as Al2O3 (i.e. sapphire) offer a near equivalent transmittance range to many of the fluoride glasses and have benefits of high melting points, chemical inertness, and the ability to be readily melted and grown in air. Chalcogenide glasses, which generally comprise one or more elements Ge, Si, As and Sb, are capable of optical transmission in both the mid-infrared and far-infrared regions.

A typical chalcogenide fiber glass is therefore arsenide trisulfide (As2S3). However, research activities into far-infrared transmission using chalcogenide glasses, halide glasses, polycrystalline halide fibers (e.g. silver and thallium) and hollow glass waveguides are primarily concerned with radiometry, infrared imaging, optical wireless, optical sensing and optical power transmission rather than telecommunications

The loss spectrum for a single-crystal sapphire fiber which also transmits in the midinfrared is also shown in Figure 2.6. Although they have robust physical properties, including a Young's modulus six times greater as well as a thermal expansion some ten times higher than that of silica, these fibers lend themselves to optical power delivery applications [Ref. 27], not specifically optical communications. Chalcogenide glasses which have their lowest losses over both the mid- and far-infrared ranges are very stable, durable and insensitive to moisture. Arsenic trisulfide fiber, being one of the simplest, has a spectral range from 0.7 to around 6 µm. Hence it has a cut off at long wavelength significantly before the chalcogenide fibers containing heavier elements such as Te, Ge and Se, an attenuation spectrum for the latter being incorporated in Figure 2.6. In general, chalcogenide glass fibers have proved to be useful in areas such as optical sensing, infrared imaging and for the production of fiber infrared lasers and amplifiers.

Dispersion

Dispersion of the transmitted optical signal causes distortion for both digital and analog transmission along optical fibers. When considering the major implementation of optical fiber transmission which involves some form of digital modulation, then dispersion mechanisms within the fiber cause broadening of the transmitted light pulses as they travel along the channel. The phenomenon is illustrated in Figure 2.7, where it may be observed that each pulse broadens and overlaps with its neighbors, eventually becoming indistinguishable at the receiver input. The effect is known as intersymbol interference (ISI). Thus an increasing number of errors may be encountered on the digital optical channel as the ISI becomes more pronounced. The error rate is also a function of the signal attenuation on the link and the subsequent signal-to-noise ratio (SNR) at the receiver.

For no overlapping of light pulses down on an optical fiber link the digital bit rate *B*T must be less than the reciprocal of the broadened (through dispersion) pulse duration (2τ).

Hence:

$$B_T \leq \frac{1}{2\tau} \tag{2.10}$$

The conversion of bit rate to bandwidth in hertz depends on the digital coding format used. For metallic conductors when a nonreturn-to-zero code is employed, the binary 1 level is held for the whole bit period τ. In this case there are two bit periods in one wavelength (i.e. 2 bits per second per hertz), as illustrated in Figure 2.8(a). Hence the maximum bandwidth *B* is one-half the maximum data rate or:

$$B_T(\max) = 2B \tag{2.12}$$

However, when a return-to-zero code is considered, as shown in Figure 2.8(b), the binary 1 level is held for only part (usually half) of the bit period. For this signaling scheme the data rate is equal to the bandwidth in hertz (i.e. 1 bit per second per hertz) and thus $BT = B$.

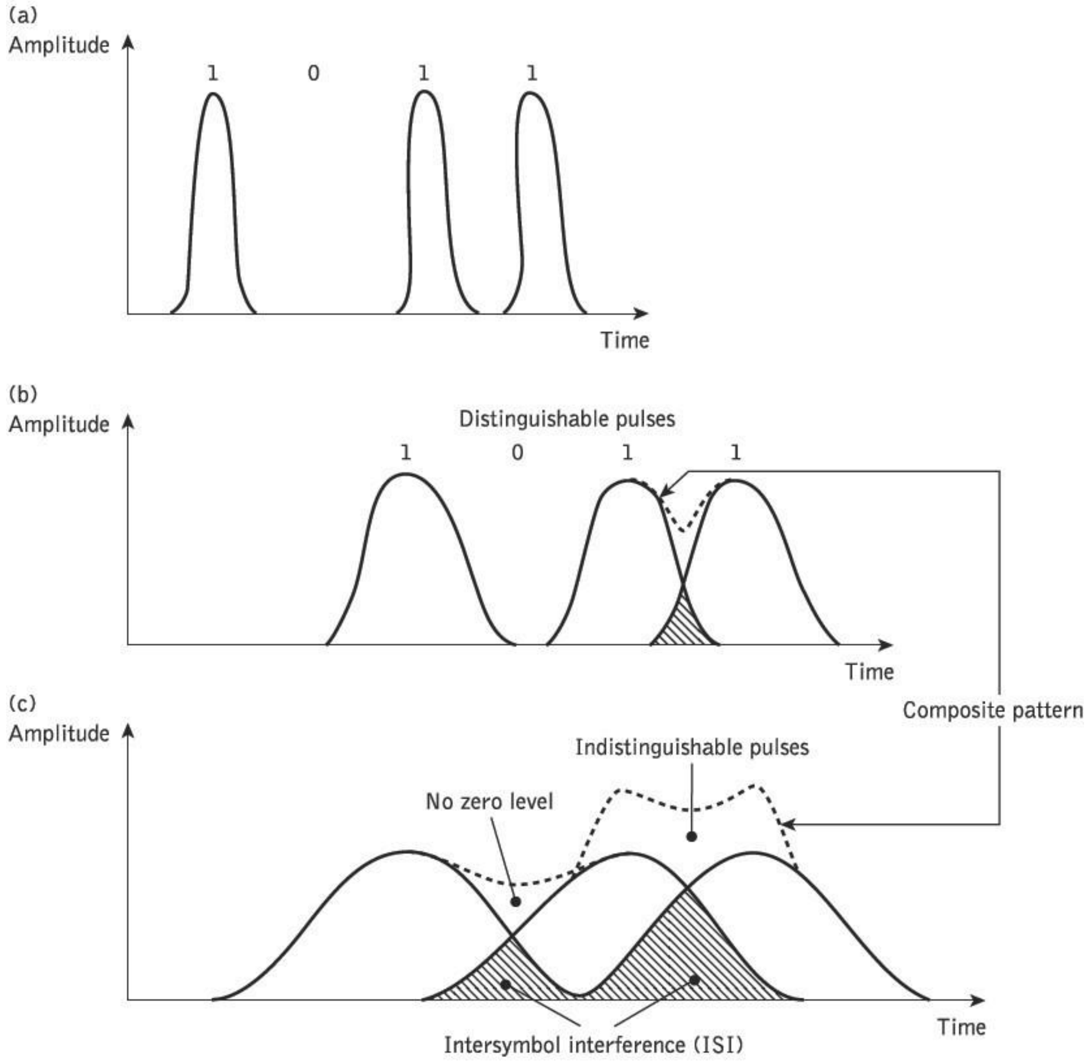


Figure 2.7 An illustration using the digital bit pattern 1011 of the broadening of light pulses as they are transmitted along a fiber: (a) fiber input; (b) fiber output at a distance $L1$; (c) fiber output at a distance $L2 > L1$

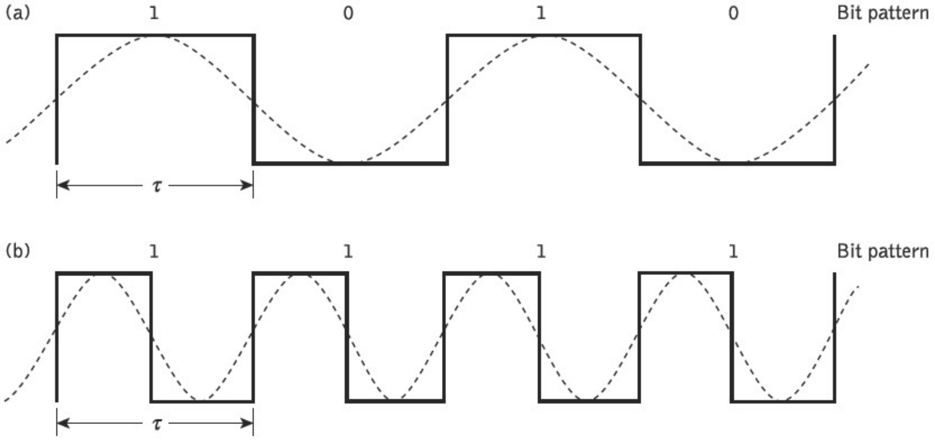


Figure 2.8 Schematic illustration of the relationships of the bit rate to wavelength for digital codes:

(a) nonreturn-to-zero (NRZ); (b) return-to-zero (RZ)

The bandwidth *B* for metallic conductors is also usually defined by the electrical 3 Db points(i.e. the frequencies at which the electric power has dropped to one-half of its constant maximum value). However, when the 3 dB optical bandwidth of a fiber is considered it is significantly larger than the corresponding 3 dB electrical bandwidth. Hence, when the limitations in the bandwidth of afiber due to dispersion are stated (i.e. optical bandwidth *B*opt), it is usually with regard to a return tozero code where the bandwidth in hertz is considered equal to the digital bit rate. Within the contextof dispersion the bandwidths expressed in this chapter will follow this general criterion unless otherwise stated.

when electro-optic devices and optical fiber systems are considered it is more usual to statethe electrical 3 dB bandwidth, this being the more useful measurement when interfacing an optical fiber link to electrical terminal equipment.

Intramodal Dispersion

Chromatic or intramodal dispersion may occur in all types of optical fiber and results from the finite spectral linewidth of the optical source. Since optical sources do not emit just a single frequency but a band of frequencies (in the case of the injection laser corresponding to only a fraction of a percent of the center frequency, whereas for the LED it is likely to be a significant percentage), then there may be propagation delay differences between the different spectral components of the transmitted signal. This causes broadening of each transmitted mode and hence intramodal dispersion. The delay differences may be caused by the dispersive properties of the waveguide material (material dispersion) and also guidance effects within the fiber structure (waveguide dispersion).

Material dispersion

Pulse broadening due to material dispersion results from the different group velocities of the various spectral components launched into the fiber from the optical source. It occurs when the phase velocity of a plane wave propagating in the dielectric medium varies nonlinearly with wavelength, and a material is said to exhibit material dispersion when the second differential of the refractive index with respect to wavelength is not zero.

Hence the group delay is given by:

$$\tau_g = \frac{d\beta}{d\omega} = \frac{1}{c}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right) \qquad (2.13)$$

where $n1$ is the refractive index of the core material. The pulse delay τm due to material dispersion in a fiber of length *L* is therefore:

$$\tau_m = \frac{L}{c}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right) \qquad (2.14)$$

For a source with rms spectral width σ_λ and a mean wavelength λ, the rms pulse broadening due to material dispersion σm may be obtained from the expansion of Eq. (2.14) in a

Taylor series about λ where:

$$\sigma_m = \sigma_\lambda\frac{d\tau_m}{d\lambda} + \sigma_\lambda\frac{2d^2\tau_m}{d\lambda^2} + \ldots \qquad (2.15)$$

As the first term in Eq. (2.15) usually dominates, especially for sources operating over the 0.8 to 0.9 μm wavelength range, then:

$$\sigma_m \simeq \sigma_\lambda \frac{d\tau_m}{d\lambda} \tag{2.16}$$

Hence the pulse spread may be evaluated by considering the dependence of τ_m on λ, where from Eq. (2.14):

$$\frac{d\tau_m}{d\lambda} = \frac{L\lambda}{c}\left[\frac{dn_1}{d\lambda} - \frac{d^2 n_1}{d\lambda^2} - \frac{dn_1}{d\lambda}\right]$$

$$= \frac{-L\lambda}{c}\frac{d^2 n_1}{d\lambda^2} \tag{2.17}$$

Therefore, substituting the expression obtained in Eq. (2.17) into Eq. (2.16), the rms pulse broadening due to material dispersion is given by:

$$\sigma_m \simeq \frac{\sigma_\lambda L}{c}\left|\lambda \frac{d^2 n_1}{d\lambda^2}\right| \tag{2.18}$$

The material dispersion for optical fibers is sometimes quoted as a value for $|\lambda^2(d^2 n_1/d\lambda^2)|$ or simply $|d^2 n_1/d\lambda^2|$.

However, it may be given in terms of a material dispersion parameter *M* which is defined as:

$$M = \frac{1}{L}\frac{d\tau_m}{d\lambda} = \frac{\lambda}{c}\left|\frac{d^2 n_1}{d\lambda^2}\right| \tag{2.19}$$

and which is often expressed in units of ps nm−1 km−1.

Waveguide dispersion

The waveguiding of the fiber may also create chromatic dispersion. This results from the variation in group velocity with wavelength for a particular mode. Considering the ray theory approach, it is equivalent to the angle between the ray and the fiber axis varying with wavelength which subsequently leads to a variation in the transmission times for the rays, and hence dispersion. For a single mode whose propagation constant is β, the fiber exhibits waveguide dispersion when $d^2\beta/d\lambda^2 \neq 0$. Multimode fibers, where the majority of modes propagate far from cutoff, are almost free of waveguide dispersion and it is generally negligible compared with material dispersion (≈0.1 to 0.2 ns/ km).

However, with single-mode fibers where the effects of the different dispersion mechanisms are not easy to separate, waveguide dispersion may be significant.

Intermodal dispersion

Pulse broadening due to intermodal dispersion (sometimes referred to simply as modal or mode dispersion) results from the propagation delay differences between modes within a multimode fiber. As the different modes which constitute a pulse in a multimode fiber travel along the channel at different group velocities, the pulse width at the output is dependent upon the transmission times of the slowest and fastest modes. This dispersion mechanism creates the fundamental difference in the overall dispersion for the three types of fiber. Thus multimode step index fibers exhibit a large amount of intermodal dispersion which gives the greatest pulse broadening. However, intermodal dispersion in multimode fibers may be reduced by adoption of an optimum refractive index profile which is provided by the near-parabolic profile of most graded index fibers.

Hence, the overall pulse broadening in multimode graded index fibers is far less than that obtained in multimode step index fibers (typically by a factor of 100). Thus graded index fibers usedwith a multimode source give a tremendous bandwidth advantage over multimode step index fibers.Under purely single-mode operation there is no intermodal dispersion and therefore pulse broadeningis solely due to the intramodal dispersion mechanisms. In theory, this is the case with single-mode step index fibers where only a single mode is allowed to propagate. Hence they exhibit the least pulse broadening and have the greatest possible bandwidths, but in general are only usefully operated withsingle-mode sources.

In order to obtain a simple comparison for intermodal pulse broadening between multimode step index and multimode graded index fibers, it is useful to consider the geometric optics picture forthe two types of fiber.

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 travel along the fiber is known as **group velocity**. Group velocity is given by,

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

Thus, different frequency components in a signal will travel at different group velocities and so will arrive at their destination at different times, for digital modulation of carrier, this results in dispersion of pulse, which affects the maximum rate of modulation. Let the difference in propagation times for two side bands is δτ.

Information Capacity Determination

Dispersion and attenuation of pulse travelling along the fiber is shown in Fig. 2.6.1. Fig. 2.6.1 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.

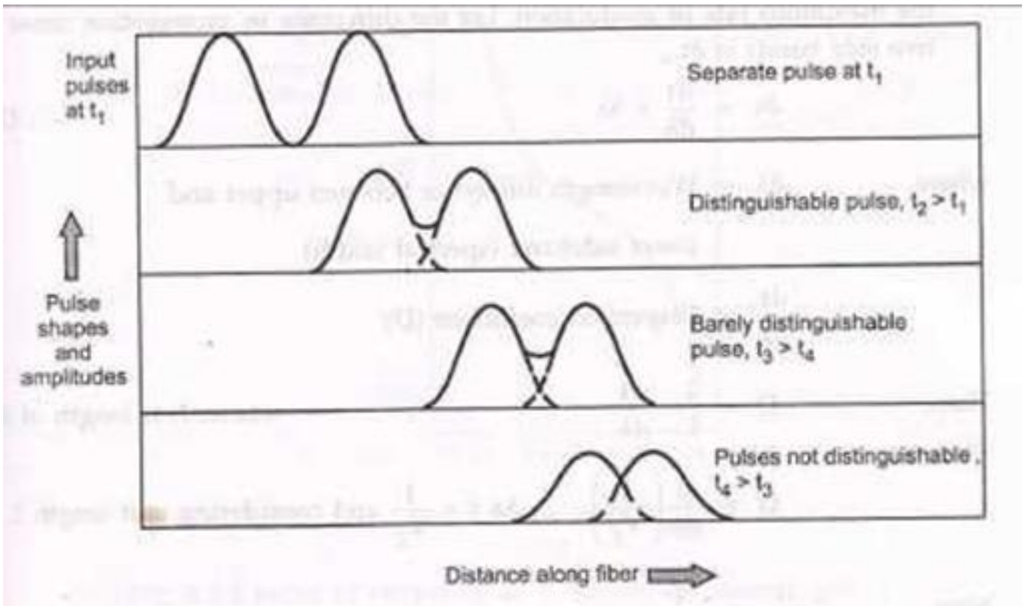
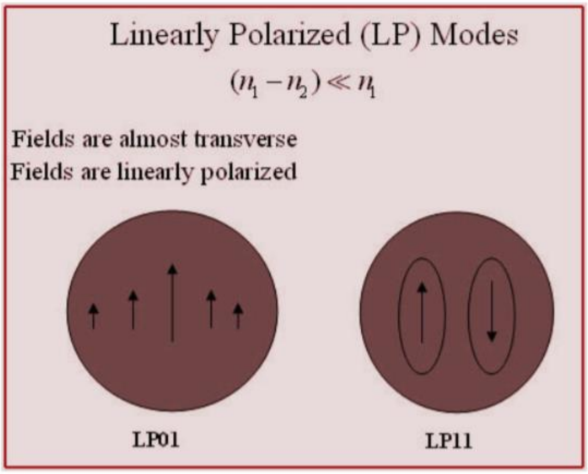


Fig. 2.6.1 Dispersion and attenuation in fiber

Polarization Mode Dispersion

- As the name suggests, the polarization mode dispersion is due unequal velocities of two orthogonal states of polarization.
- The difference in the propagation time between two orthogonal polarization mode will result in pulse spreading.
- The PMD puts the ultimate restriction on the data rate on the long haul single mode optical fiber.

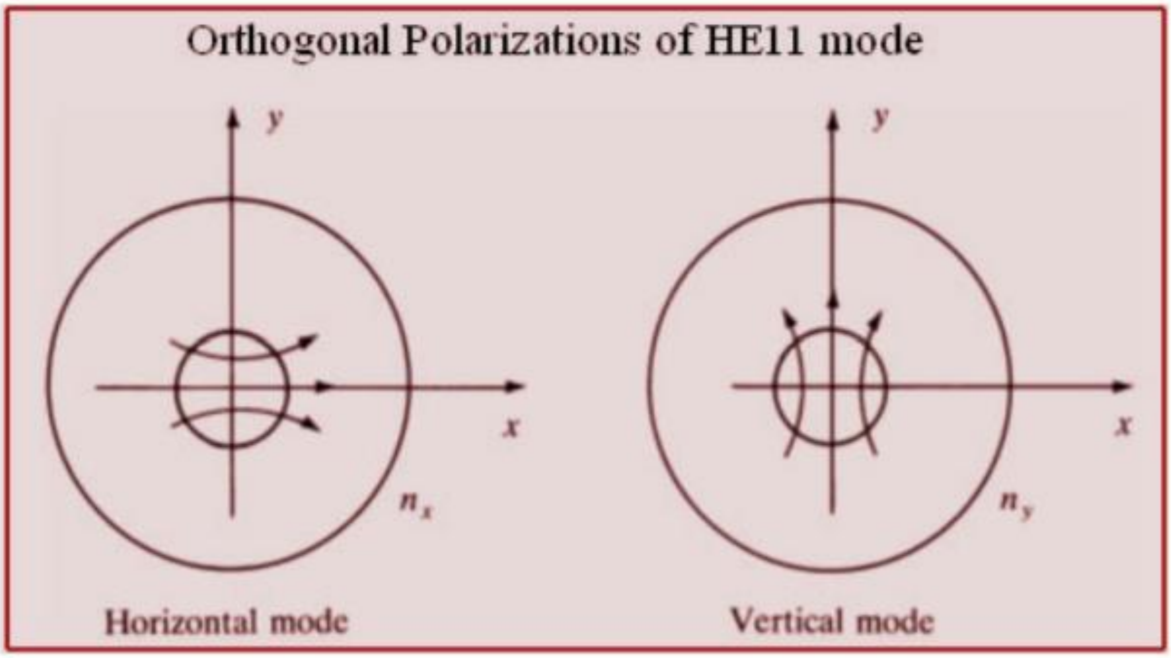
- **In the weekly guiding approximation i.e. when $(n_1 - n_2) \ll n_1$, The lowest order HE_{11} mode becomes a linearly polarized , LP_{01} mode. That is over the cross-section of the fiber core the field has same direction. See Fig.**


Linearly Polarized (LP) Modes

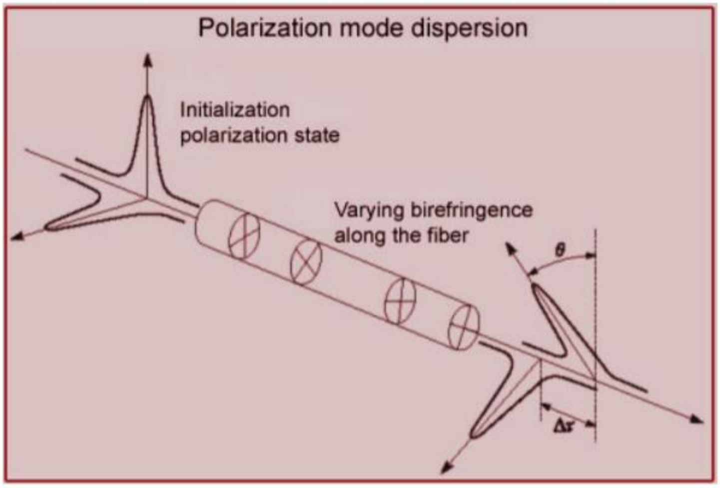
$(n_1 - n_2) \ll n_1$

Fields are almost transverse
Fields are linearly polarized

- A linearly polarized field can be resolved into two orthogonally polarized fields The pulse energy gets divided into two polarization states as shown in Fig.
-



- Due non-uniformity of the core-radius the effective modal index is different for the two polarizations.
- The difference in modal indices for two polarization is called the birefringence of the fiber.
- The polarizations consequently travel with different velocities, splitting optical pulse in to two.
- This phenomenon is called Polarization Mode Dispersion .
- No one polarization systematically sees the same modal index.
- The optical pulse therefore has statistical fluctuation of the polarization.
- The pulse slowly broadens due to the statistical fluctuation of the velocities of the two orthogonal polarizations.



Modal Birefringence:

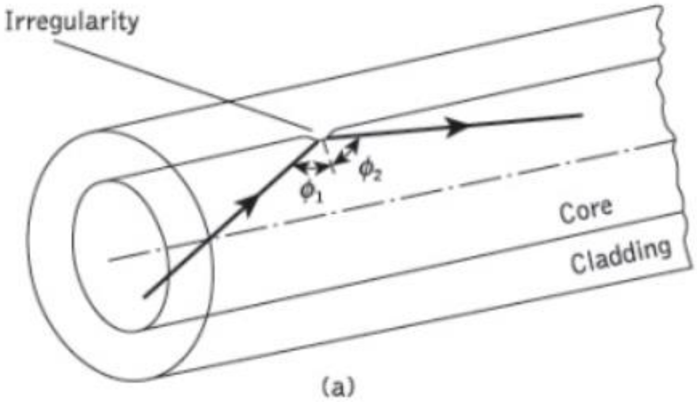
- Birefringence is a term used to describe a phenomenon that occurs in certain types of materials, in which light is split into two different paths. This phenomenon occurs because these materials have different indices of refraction, depending on the polarization direction of light.
- Birefringence is also observed in an optical fiber, due to the slight asymmetry in the fiber core cross-section along the length and due to external stresses applied on the fiber such as bending.

Fiber Beat Length:

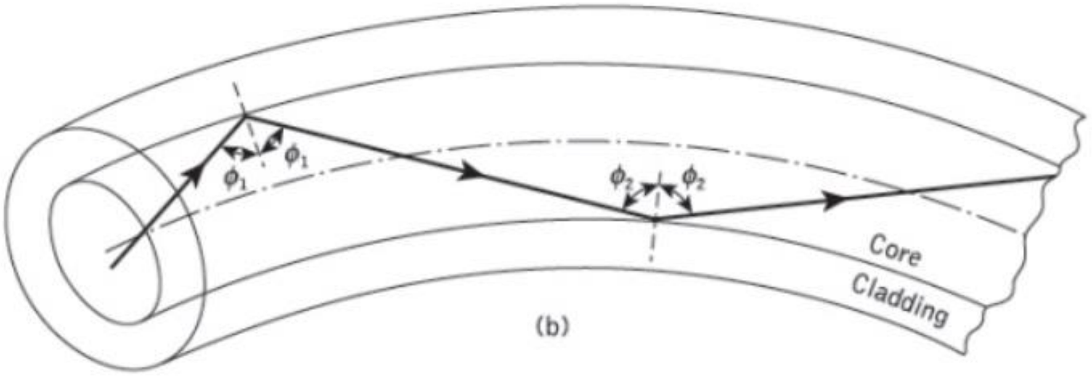
- A characteristic of optical fiber used to calculate the fiber's ability to maintain polarization.
- The beat length describes the length required for the polarization to rotate 360 degrees.
- For a given wavelength, it is inversely proportional to the fiber's birefringence.

Mode Coupling:

- After a certain initial length, the pulse distortion increases less rapidly because of mode coupling and differential mode loss
- waveguide perturbations such as deviations of the fiber axis from straightness, variations in the core diameter, irregularities at the core–cladding interface and refractive index variations may change the propagation characteristics of the fiber.
- These will have the effect of coupling energy traveling in one mode to another depending on the specific perturbation.
- Ray theory aids the understanding of this phenomenon, as shown in Figure



(a)



(b)

Cut off Wavelength:

- One of the important transmission parameter for single mode fiber is cut off wavelength for the higher order mode (LP11)
- It separates the single mode and multimode regions
- a theoretical cutoff wavelength λc given by:
-

$$\lambda_c = \frac{2\pi a n_1}{v_c}(2\Delta)^{\frac{1}{2}}$$

- Where *V*c is the cut off normalized frequency. Hence λc is the wavelength above which a particular fiber becomes single-moded.
- Vc=2.405 for step index fiber
- The relationship between cut off wavelength and cut off normalized frequency is given as

$$\frac{\lambda_c}{\lambda} = \frac{V}{V_c}$$

Thus for the step index fiber Vc =2.405, the cut off wavelength is given by

$$\lambda_c = \frac{V\lambda}{2.405}$$

Single-Mode Fiber Design Considerations:

- The parameters that are important for the design of a single-mode fiber are
- (i) cutoff wavelength,
- (ii) fiber loss,
- (iii) dispersion,
- (iv) dispersion slope,
- (v) polarization mode dispersion, and
- (vi) spot size
- Using a step-index optical fiber, it is not possible to optimize all these parameters.
- Therefore, the refractive index profile *n*(*r*) is chosen so that the design parameters listed above are optimum for a specific application.

UNIT III FIBER OPTICAL SOURCES AND COUPLING

- Direct and indirect Band gap Materials
- LED structures -Light source materials
- Quantum efficiency and LED power
- Modulation of a LED
- lasers Diodes-Modes and Threshold condition
- Rate equations-
- External Quantum efficiency
- Resonant frequencies
- Laser Diodes
- Temperature effects
- Introduction to Quantum laser
- Fiber amplifiers
- Power Launching and coupling
- Lencing schemes,
- Fiber -to- Fiber joints
- Fiber splicing-Signal to Noise ratio
- Detector response time.

Introduction

- Emission of light, (in the form of a photon) can take place either spontaneously or it can be stimulated by the presence of another photon of the right energy level.
- For spontaneous or stimulated emission to occur, energy must be supplied to boost the electron from its low energy state to a higher energy state.
- The energy can come from many sources: Heat (Incandescent light), Electrical Discharge (D_2, Hg, Na lamps), Electrical Current (LED, LD), Bioluminescence (Fire fly- luciferase enzyme)

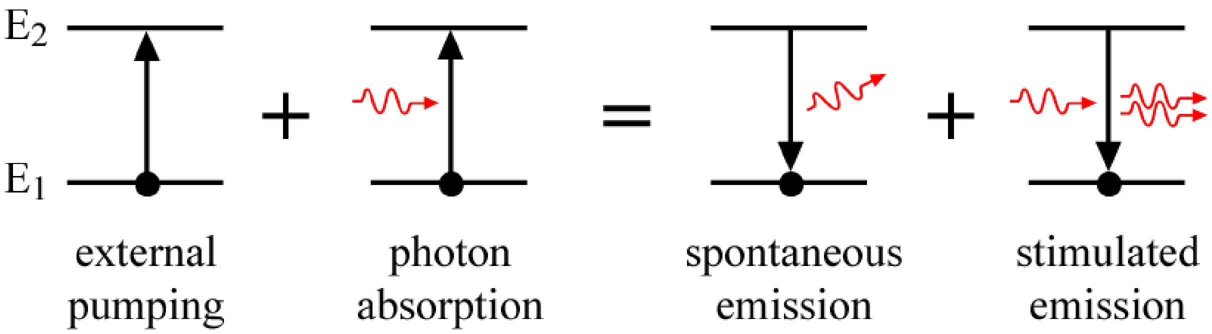
Optical Source Requirement for Performance (For Fiber Optics)

- Physical dimensions to suit the optical fiber
- Narrow radiation pattern (beam width)
- Linearity (output light power proportional to driving current)
- Ability to be directly modulated by varying driving current
- Fast response time
- Adequate output power into the fiber
- Narrow spectral width (or line width)
- Stability and efficiency
- Driving circuit issues
- Reliability and cost
- Almost all these requirements are satisfied by LED and Laser diodes. Both are working in forward biased mode

Semiconductor Materials

- Two energy bands
  - Conduction band (CB)
  - Valence band (VB)
- Fundamental processes
  - Absorbed photon creates an electron-hole pair
  - Recombination of an electron and hole can emit a photon
- Types of photon emission
  - **Spontaneous emission**
    - Random recombination of an electron-hole pair
    - Dominant emission for light emitting diodes (LED)
  - **Stimulated emission**
    - A photon excites another electron and hole to recombine
    - Emitted photon has similar wavelength, direction, and phase
    - Dominant emission for laser diodes

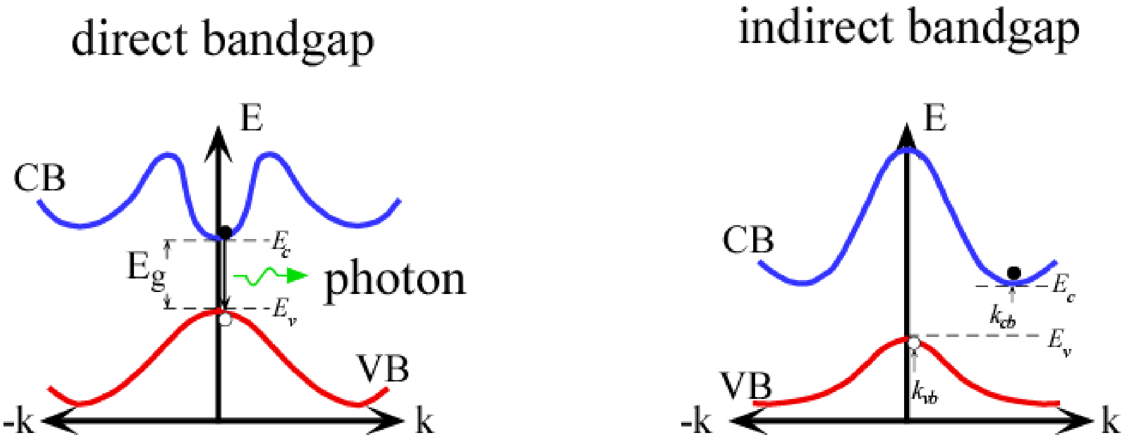
Basic Light Emission Processes



- Pumping (creating more electron-hole pairs)
  - Electrically create electron-hole pairs
  - Optically create electron-hole pairs
- Emission (recombination of electron-hole pairs)

        - Spontaneous emission
        - Simulated emission

Direct and Indirect Materials



(a) GaAs (b) Si

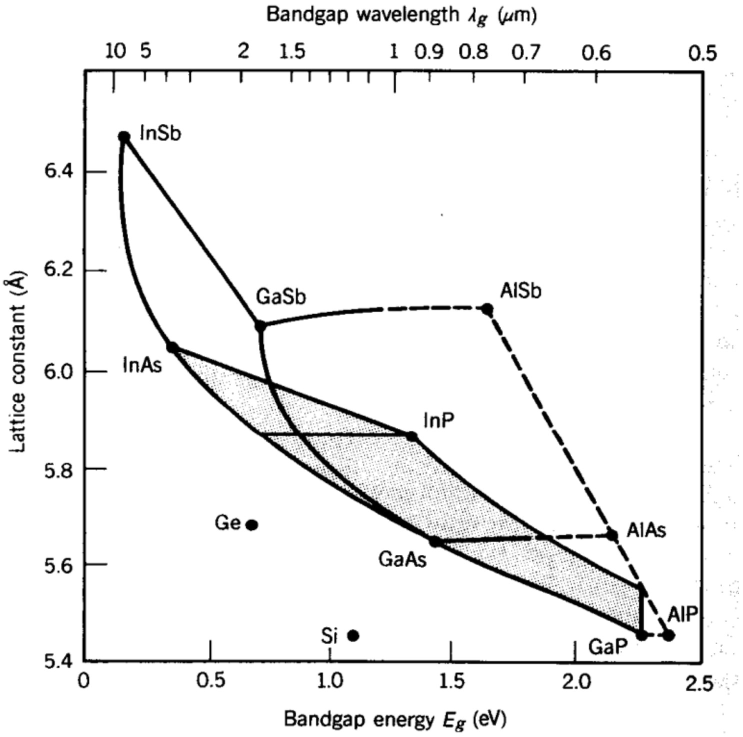
- Relationship between energy and momentum for electrons and holes
    - Depends on the material
- Electrons in the CB combine with holes in the VB
- Photons have no momentum
    - Photon emission requires no momentum change
    - CB minimum needs to be directly over the VB maximum
    - **Direct bandgap transition required**
- Only specific materials have a direct bandgap
- The emission wavelength depends on the energy band gap

$$E_g = E_2 - E_1$$

$$\lambda = \frac{hc}{E_g} = \frac{1.24}{E_g(eV)}(\mu m)$$

- Semiconductor compounds have different
    - Energy band gaps
    - Atomic spacing (called lattice constants)
- Combine semiconductor compounds
    - Adjust the bandgap
    - Lattice constants (atomic spacing) must be matched
    - Compound must be matched to a substrate
        - Usually GaAs or InP
- Only specific materials have a direct bandgap
- Material determines the bandgap

Material	**Element Group**	**Bandgap Energy E_g (eV)**	**Bandgap wavelength l_g (mm)**	**Type**
Ge	IV	0.66	1.88	I
Si	IV	1.11	1.15	I
AlP	III-V	2.45	0.52	I
AlAs	III-V	2.16	0.57	I
AlSb	III-V	1.58	0.75	I
GaP	III-V	2.26	0.55	I
GaAs	III-V	1.42	0.87	D
GaSb	III-V	0.73	1.70	D
InP	III-V	1.35	0.92	D
InAs	III-V	0.36	3.5	D
AnSb	III-V	0.17	7.3	D



Common Semiconductor Compounds

- GaAs and AlAs have the same lattice constants
    - These compounds are used to grow a ternary compound that is lattice matched to a GaAs substrate ($Al_{1-x}Ga_xAs$)
    - 0.87 < l < 0.63 (mm)
- Quaternary compound $Ga_xIn_{1-x}As_yP_{1-y}$ is lattice matched to InP if y=2.2x
    - 1.0 < l < 1.65 (mm)
- Optical telecommunication laser compounds
    - $In_{0.72}Ga_{0.28}As_{0.62}P_{0.38}$ (l=1300nm)

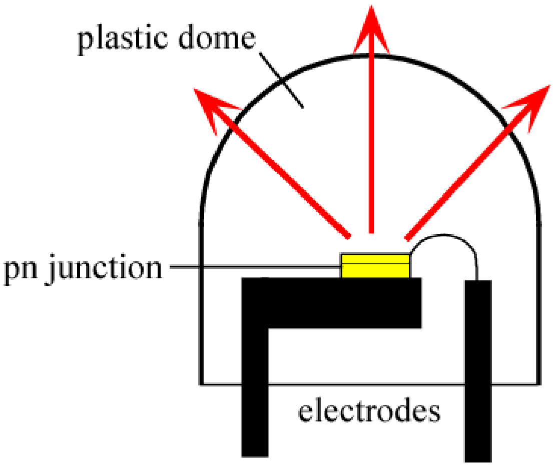
$In_{0.58}Ga_{0.42}As_{0.9}P_{0.1}$ (l=1550nm)

Optical Sources

- Two main types of optical sources
    - Light emitting diode (LED)
        - Large wavelength content
        - Incoherent
        - Limited directionality
    - Laser diode (LD)
        - Small wavelength content
        - Highly coherent
        - Directional

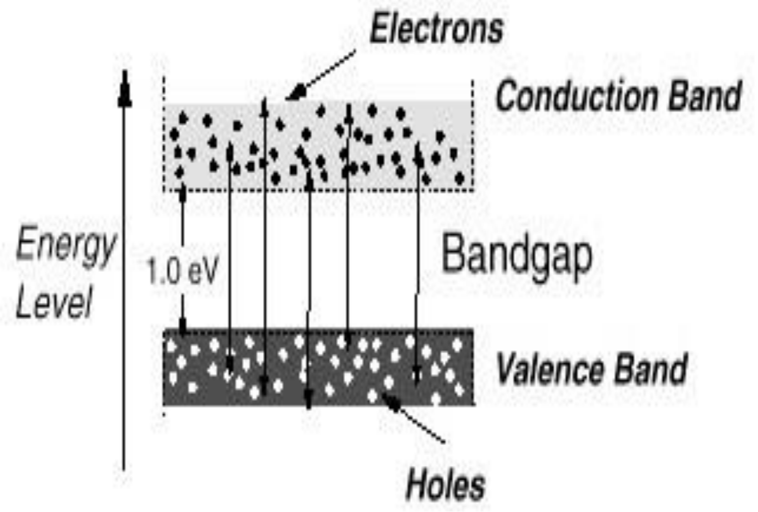
Light Emitting Diodes (LED)

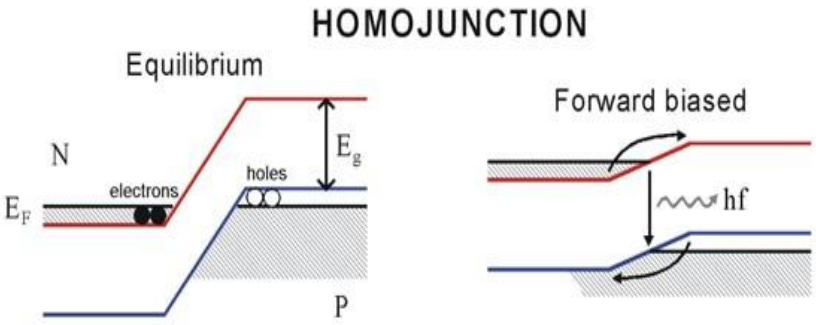
- Spontaneous emission dominates
    - Random photon emission
- Implications of random emission
    - Broad spectrum (Dl~30nm)
    - Broad far field emission pattern
- Dome used to extract more of the light
    - Critical angle is between semiconductor and plastic
    - Angle between plastic and air is near normal
    - Normal reflection is reduced
    - Dome makes LED more directional



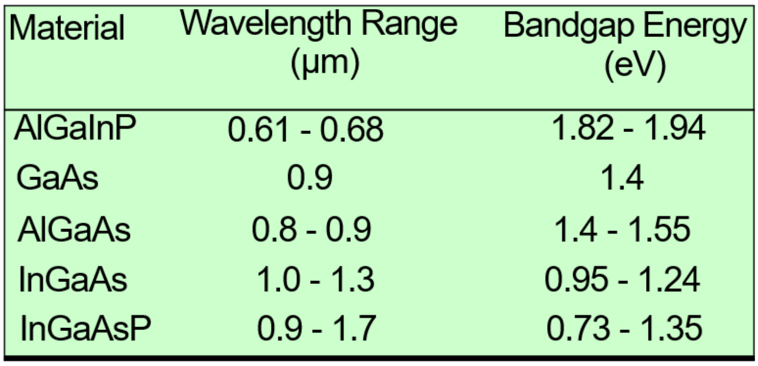
Basic LED operation

- A PN junction acts as the active or recombination region.
- When the PN junction is forward biased, electrons and holes recombine either radiatively (emitting photons) or non-radiatively (emitting heat). This is simple LED operation.





- Emitted wavelength depends on bandgap energy Transitions can take place from any energy state in either band to any state in the other band. This results in a range of different wavelengths produced in this spontaneous emission. This accounts for the fact that LEDs produce a range of wavelengths. Typically, the range is about 80 nm or so.



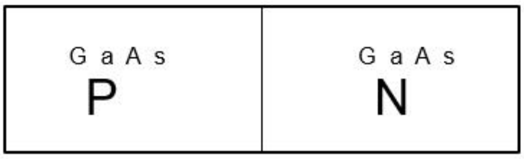
Material	Wavelength Range (μm)	Bandgap Energy (eV)
AlGaInP	0.61 - 0.68	1.82 - 1.94
GaAs	0.9	1.4
AlGaAs	0.8 - 0.9	1.4 - 1.55
InGaAs	1.0 - 1.3	0.95 - 1.24
InGaAsP	0.9 - 1.7	0.73 - 1.35

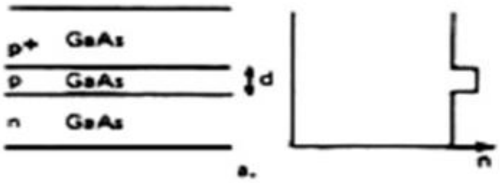
LED-Principle of Operation

- LED can be used in fiber transmission applications, it must have
- High radiance output or brightness:
- Measure of optical power radiated into a unit solid angle per unit area of the emitting surface
- Fast emission response time:

- It is a time delay between the application of a current pulse and respective optical emission
- High quantum efficiency
- it is related to the fraction of the electron hole pairs that recombine radiatively
- LED structure should provide a high radiance and a high quantum efficiency.
- It must achieve carrier and optical confinement
- Types:
- Homojunctions structure
- Heterojunctions structure

Homojunctions: P- type and N-type from same material





Structure and index of refraction n in gallium arsenide with a junction width d

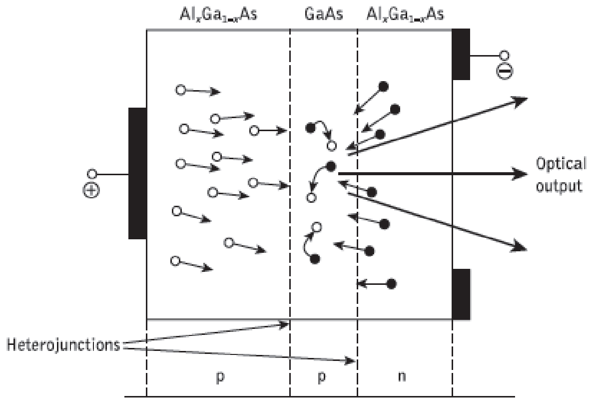
- Carriers are not confined
- Light is not confined
- LED should have a high radiance (light intensity), fast response time and a high quantum efficiency for FO system

Heterojunctions: Different p- and n- materials

- Carriers are confined
- Light is also confined
- Single Heterojunction, Double Heterojunction.
- A heterojunction is a junction between semiconductors with different bandgap energies.

The double-heterojunction LED

The principle of operation of the DH LED is illustrated in Figure. The device shown consists of a *p*-type GaAs layer sandwiched between a *p*-type AlGaAs and an *n*-typebAlGaAs layer. When a forward bias is applied electrons from the *n*-type layer are injected through the *p*–*n* junction into the *p*-type GaAs layer where they become minority carriers.



These minority carriers diffuse away from the junction recombining with majority carriers (holes) as they do so. Photons are therefore produced with energy corresponding to the band gap energyof the *p*-type GaAs layer. The injected electrons are inhibited from diffusing into the *p*-type AlGaAs layer because of the potential barrier presented by the p–p heterojunction, Hence, electroluminescence only occurs in the GaAs junction layer, providing both good internal quantum efficiency and high-radiance emission.

Types of LED Configurations

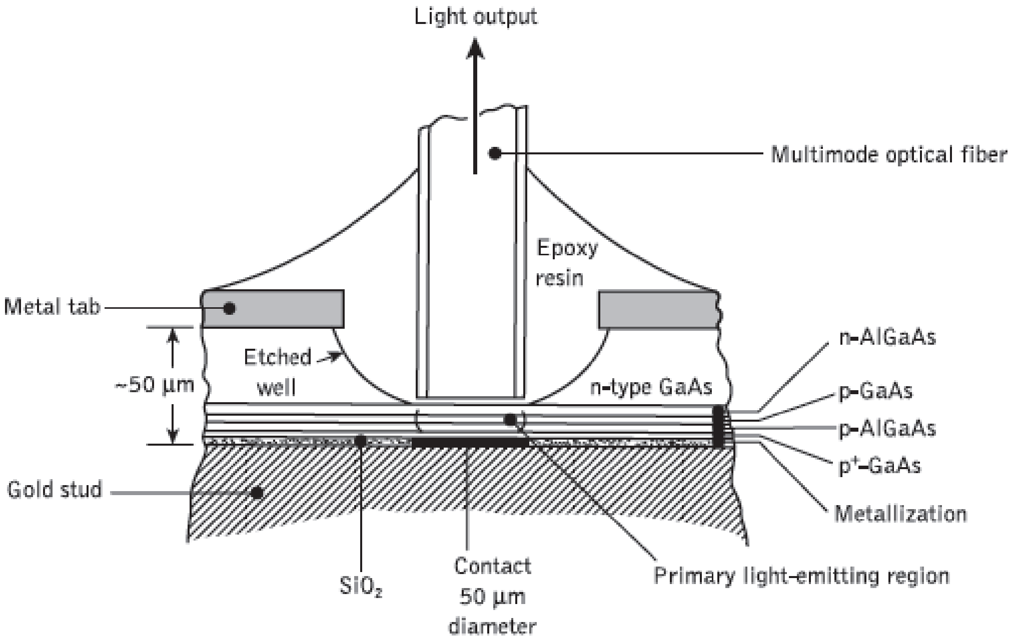
- Surface Emitting LED’s (SLED)
- Edge Emitting LED’s (EELED)
- Super luminescent LED’s (SLD)

Confining and Guiding the Light within the Device

In both types of LED (SLED and ELED) a combination of insulating materials and junctions is used to:

1. Guide the current flow to a small “active region” and
2. Guide the light produced out of the device and into an easy position for coupling to a fiber.

Surface Emitter LED



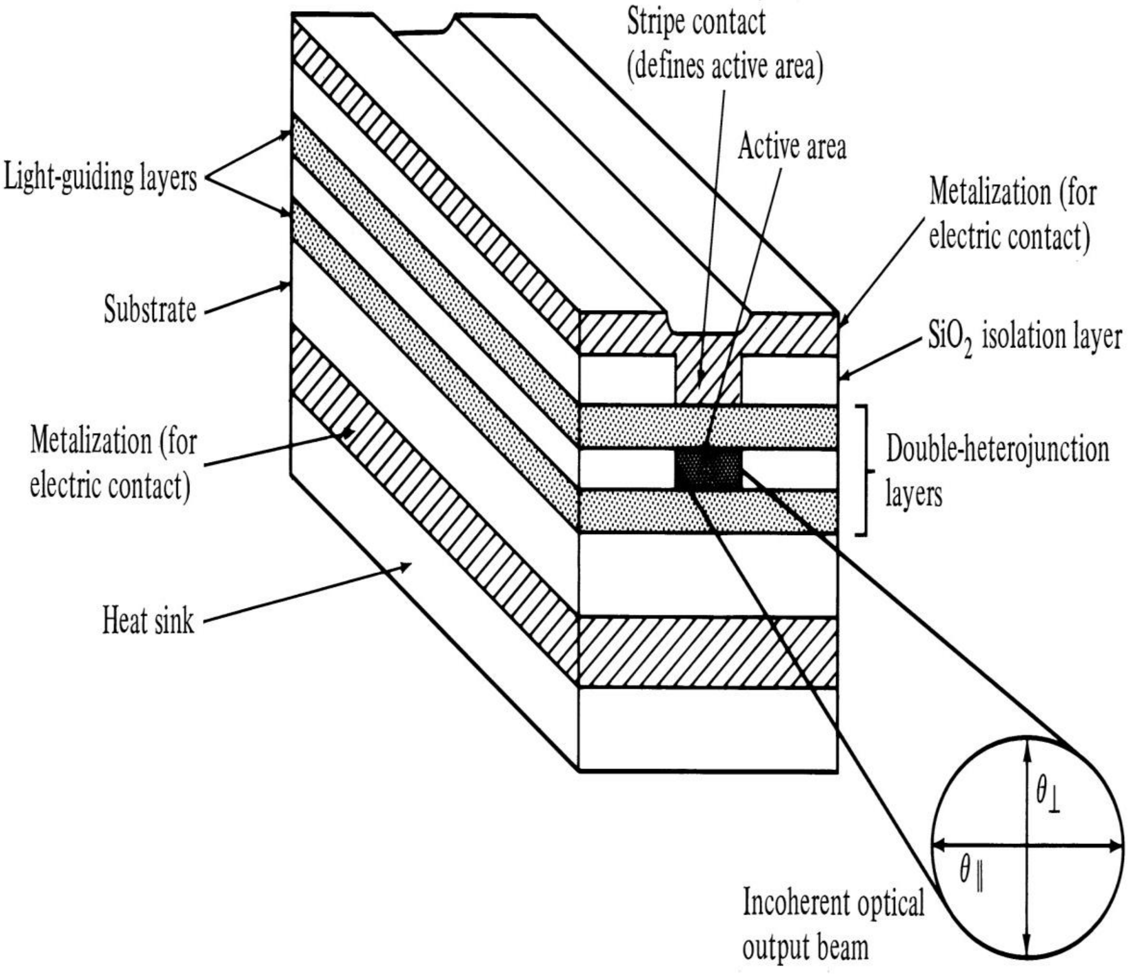
Surface emitter LED (SLED) has been widely employed within optical fiber communications in which A method for obtaining high radiance is to restrict the emission to a small active region within the device. These structures have low thermal impedance in the active region allowing high current densities and giving high- radiance emission into the optical fiber. The structure of a high-radiance etched well DH surface emitter* for the 0.8 to 0.9 μm wavelength band is shown in Figure. The internal absorption in this device is very low due to the larger band-gap-confining layers, and the reflection coefficient at the back crystal face is high giving good forward radiance. The emission from the active layer is essentially isotropic, although the external emission distribution may be considered Lambertian with a beam width of 120° due to refraction from a high to a low refractive index at the GaAs–fiber interface. The power coupled P_c into a multimode step index fiber may be estimated from the relationship:

$$P_c = \pi(1 - r)AR_D(NA)^2$$

Where r is the Fresnel reflection coefficient at the fiber surface, A is the smaller of the fiber core cross-sectionor the emission area of the source and R_D is the radiance of the source.

Edge emitter LED

Edge emitter LED (ELED) has a similar geometry to a conventional contact stripe injection laser



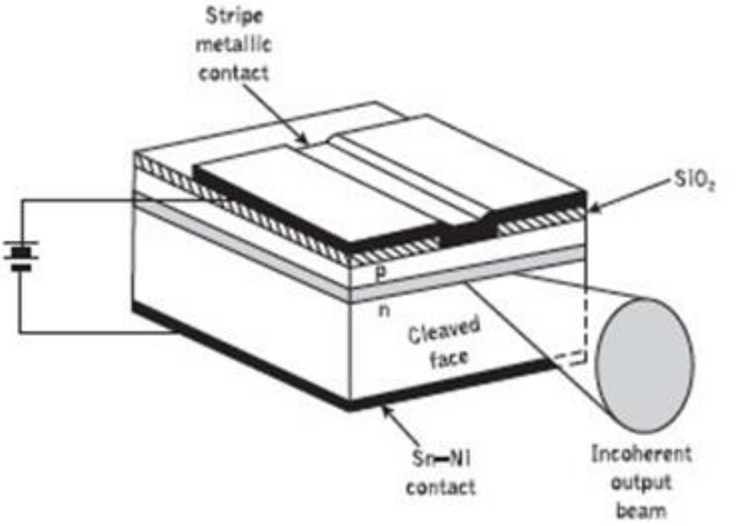
It takes advantage of transparent guiding layers with a very thin active layer (50 to 100 μm) in order that the light produced in the active layer spreads into the transparent guiding layers, reducing self-absorption in the active layer. The consequent wave guiding narrows the beam divergence to a half-power width of around 30° in the plane perpendicular to the junction. However, the lack of wave guiding in the plane of the junction gives a Lambertian output with a half-power width of around 120°.The ELED active layer was heavily doped with Zn to reduce the minority carrier lifetime and thus improve the device modulation bandwidth. In this way a 3 dB modulation bandwidth of 600 MHz was obtained. Very high coupled optical power levels into single-mode fiber in excess of 100 μW have been obtained with In GaAsP ELEDs at drive currents as low as 50 mA.

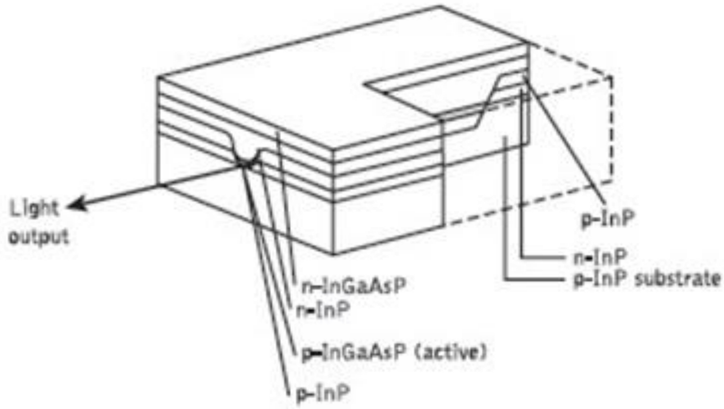
Super luminescent LED

Another device geometry which is providing significant benefits over both SLEDs and ELEDs forcommunication applications is the Super luminescent diode or SLD. This device offers advantages of:

(a) A high output power;
(b) A directional output beam; and
(c) A narrow spectral line width.

All of which prove useful for coupling significant optical power levels into optical fiber. The super radiant emission process within the SLD tends to increase the device modulation bandwidth over that of more conventional LEDs.





A Super luminescent light emitting diode is, similar to a laser diode, based on an electrically driven pn-junction that, when biased in forward direction becomes optically active and generates amplified spontaneous emission over a wide range of wavelengths. The peak wavelength and the intensity of the SLED depend on the active material composition and on the injection current level. SLEDs are designed to have high single pass amplification for the spontaneous emission generated along the waveguide but, unlike laser diodes, insufficient feedback to achieve lasing action. This is obtained very successfully through the joint action of a tilted waveguide and anti-reflection coated (ARC) facets.

LED power and efficiency

The power generated internally by an LED may be determined by consideration of the excess electrons and holes in the *p*- and *n*-type material respectively. When it is forward biased and carrier injection takes place at the device contacts. The excess density of electrons Δn and holes Δp is equal since the injected carriers are created and recombined in pairs such that charge neutrality is maintained within the structure. In extrinsic materials one carrier type will have a much higher concentration than the other and hence in the *p*-type region, for example, the hole concentration will be much greater than the electron concentration. Generally, the excess minority carrier density decays exponentially with time t according to the relation:

$$\Delta n = \Delta n(0) \exp(-t/\tau) \quad (1)$$

where $\Delta n(0)$ is the initial injected excess electron density and τ represents the total carrier recombinationlifetime.

When there is a constant current flow into the junction diode, an equilibrium conditionis established. In thiscase, the total rate at which carriers are generated will be the sum of the externally supplied and the thermal generation rates. Hence a rateequation for carrier recombination in theLED can be expressed in the form

$$\frac{d(\Delta n)}{dt} = \frac{J}{ed} - \frac{\Delta n}{\tau} \quad (\mathrm{m^{-3}\,s^{-1}})$$

.......(2)

The condition for equilibrium is obtained by setting the derivative in Eq. (2) to zero. Hence:

$$\Delta n = \frac{J\tau}{ed} \quad (\mathrm{m^{-3}})$$

.... (3)

Equation (3) therefore gives the steady-state electron density when a constant current isflowing into the junctionregion.

It is also apparent from Eq. (2) that in the steady state the total number of carrierrecombinations per second orthe recombination rate rt will be:

$$r_t = \frac{J}{ed} \quad (\mathrm{m^{-3}})$$

$$= r_r + r_{nr} \quad (\mathrm{m^{-3}})$$

(5)

where$r$r is the radiative recombination rate per unit volume and $r$nr is the non-radiativerecombination rate per unit volume. Moreover, when the forward-biased current into thedevice is *i*, then from Eq. (7.4) the total number of recombinations per second Rt becomes:

$$R_t = \frac{i}{e}$$

(6)

The LED internal quantum efficiency* ηint, which can be defined as the ratio of theradiative recombination rateto the total recombination rate,

$$\eta_{int} = \frac{r_r}{r_t} = \frac{r_r}{r_r + r_{nr}}$$

(8)

$$= \frac{R_r}{R_t}$$

Where *R*r is the total number of *radiative* recombination per second. Rearranging Eq. (8) and substituting fromEq. (6) gives:

$$R_r = \eta_{int} \frac{i}{e} \qquad (9)$$

Since *R*r is also equivalent to the total number of photons generated per second each photon has an energy equalto *hf*joules, then the optical power generated internally by the LED, *P*int, is:

$$P_{int} = \eta_{int} \frac{i}{e} hf \quad (W)$$

the internally generated power in terms of wavelength ratherthan frequency gives:

$$P_{int} = \eta_{int} \frac{hci}{e\lambda} \quad (W)$$

For the exponential decay of excess carriers depicted by Eq. (1) the radiative minority carrier lifetime is τr =Δ*n*/*r*r and the non-radiative minority carrier lifetime is τnr = Δ*n*/rnr.Therefore, from Eq. (7.7) the internal quantum efficiency is:

$$\eta_{int} = \frac{1}{1 + (r_{nr}/r_r)} = \frac{1}{1 + (\tau_r/\tau_{nr})}$$

Furthermore, the total recombination lifetime τ can be written as τ = Δ*n*/*r*tgives:

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

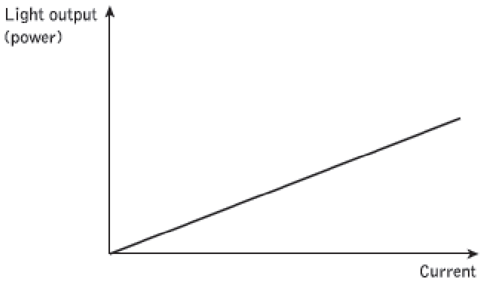
Hence,

$$\eta_{int} = \frac{\tau}{\tau_r}$$

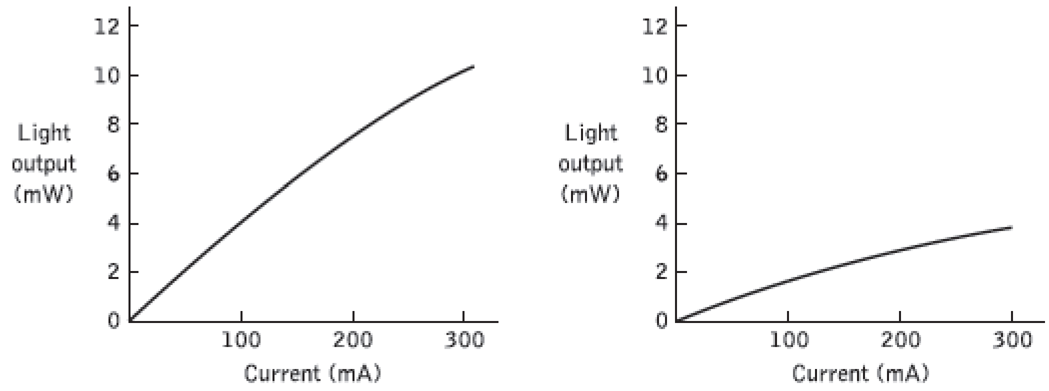
LED Characteristics

Optical output power

LED is a very linear device in comparison with the majority of injection lasers and hence it tends to be more suitable for analog transmission where severe constraints are put on the linearity of the optical source. However, in practice LEDs do exhibit significant nonlinearities which depend upon the configuration utilized. It is therefore often necessary to use some form of linear circuit technique in order to ensure the linear performance of the device to allow its use in high-quality analog transmission systems.



(a) Ideal LED characteristics

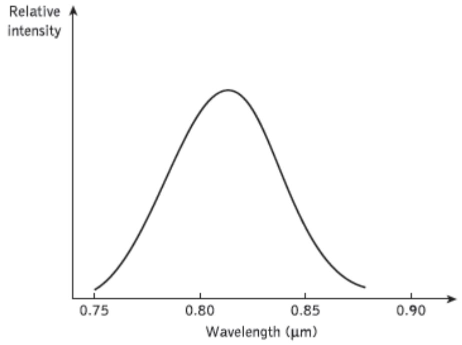


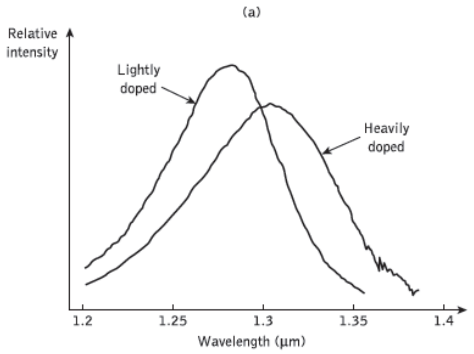
(b) Surface emitter with a 50 μm diameter dot (c) Edge emitter with a 65 μm
wide stripe and 100 μm lengthContact

Light output temperature dependence for three important LED structures emitting at a wavelength of **1.3 μm**

Output spectrum

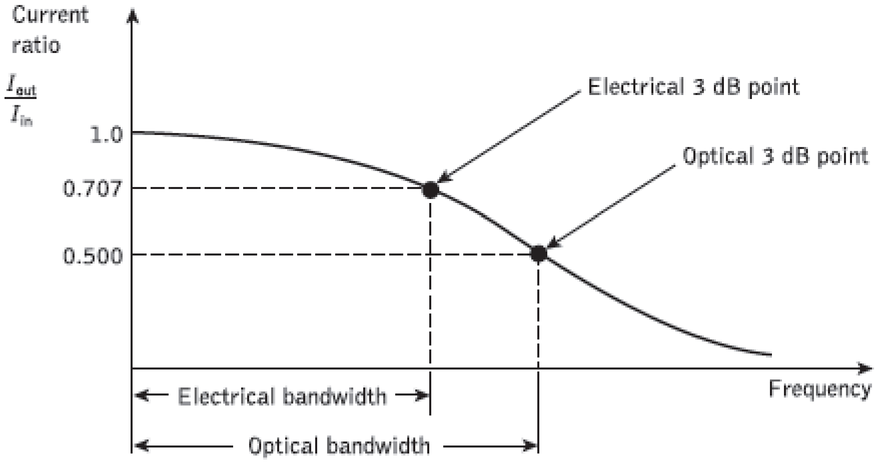
The spectral line width of an LED operating at room temperature in the 0.8 to 0.9 μm wavelength band is usually between 25 and 40 nm at the half maximum intensity points. For materials with smaller band gap energies operating in the 1.1 to 1.7 μm wavelength region the line width tend to increase to around50 to 160 nm.Examples of these two output spectra are shown in Figure. The increases in line width are due to increased doping levels and the formation of band tail states. This becomes apparent in the differences in the output spectra between surface- and edge-emitting LEDs where the devices have generally heavily doped and lightly doped.





Modulation bandwidth

The modulation bandwidth in optical communications may be defined in either electrical or optical terms. Whenthe associated electrical circuitry in an optical fiber communication system to use the electrical definition wherethe electrical signal power has dropped to half its constant value due to the modulated portion of the optical signal. This corresponds to the electrical 3 dB point or the frequency at which the output electric power is reduced by 3 dB with respect to the input electric power. Alternatively, if the 3 dB bandwidth of the modulated optical carrier (optical bandwidth)is considered, we obtain an increased value for the modulation bandwidth.



OPTICAL SOURCE: LASER

In optical Communication three main types of optical light source are available. These are:
(a) Wideband ‘continuous spectra’ sources (incandescent lamps);
(b) Monochromatic incoherent sources (light-emitting diodes, LEDs);
(c) Monochromatic coherent sources (lasers).

The major requirements for an optical fiber emitter which are outlined below:

1. A size and configuration compatible with launching light into an optical fiber. Ideally, the light output shouldbe highly directional.

2. Must accurately track the electrical input signal to minimize distortion and noise. Ideally, the source shouldbe linear.

3. Should emit light at wavelengths where the fiber has low losses and low dispersion and where the detectorsare efficient.

4. Preferably capable of simple signal modulation over a wide bandwidth extending from audio frequencies tobeyond the gigahertz range.

5. Must couple sufficient optical power to overcome attenuation in the fiber plus additional connector losses andleave adequate power to drive the detector.

6. Should have a very narrow spectral bandwidth in order to minimize dispersion in the fiber.

7. Must be capable of maintaining a stable optical output which is largely unaffected by changes in ambientconditions (e.g. temperature).

8. It is essential that the source is comparatively cheap and highly reliable in order to compete withconventional transmission techniques.

A **laser** is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The term "laser" originated as an acronym for "**light amplification by stimulated emission of radiation**". A laser differs from other sources of light because it emits light *coherently*. Lasers have many important applications. They are used in common consumer devices such as optical disk drives, laser printers, and barcode scanners. Lasers are used for both fiber-optic and free-space optical communication.

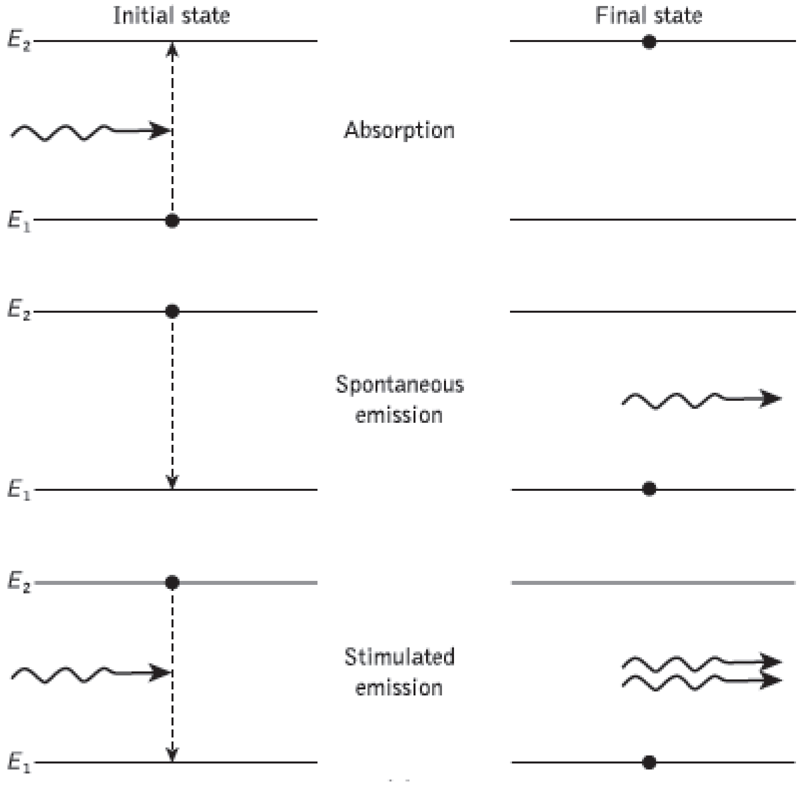
Basic Concepts

Absorption and emission of radiation

The interaction of light with matter takes place in discrete packets of energy or quanta, called photons. Furthermore, the quantum theory suggests that atoms exist only in certain discrete energy states such that absorption and emission of light causes them to make a transition from one discrete energy state to another. Thefrequency of the absorbed or emitted radiation f is related to the difference in energy E between the higher energy state$E2$ and the lower energy state $E1$ by the expression:

$$E = E2 - E1 = hf$$

Where $h = 6.626 \times 10-34$ J s is Planck's constant. These discrete energy states for the atom may be considered to correspond to electrons occurring in particular energy levels relative to the nucleus. Hence, different energy states for the atom correspond to different electron configurations, and a single electron transition between two energy levels within the atom will provide a change in energy suitable for the absorption or emission of a photon.



This emission process can occur in two ways:

(a) By spontaneous emission in which the atom returns to the lower energy state in an entirely random manner;

(b) By stimulated emission when a photon having an energy equal to the energy difference between the two states ($E2 - E1$) interacts with the atom in the upper energy state causing it to return to the lower state with the creation of a second photon.

It is the stimulated emission process which gives the laser its special properties as an optical source. The photonproduced by stimulated emission is generally of an identical energy to the one which caused it and hence the light associated with them is of the same frequency. The light associated with the stimulating and stimulated photon is in phase and has the same polarization. Therefore, in contrast to spontaneous emission, coherent radiation is obtained.

The Einstein relations

In 1917 Einstein demonstrated that the rates of the three transition processes of absorption, spontaneousemission and stimulated emission were related mathematically. He achieved this by considering the atomic system to be in thermal equilibrium such that the rate of the upward transitions must equal the rate of the downward transitions. The population of the two energy levels of such a system is described by Boltzmann statistics which give:

$$\frac{N_1}{N_2} = \frac{g_1 \exp(-E_1/KT)}{g_2 \exp(-E_2/KT)} = \frac{g_1}{g_2} \exp(E_2 - E_1/KT)$$

$$= \frac{g_1}{g_2} \exp(hf/KT)$$

Where $N1$ and $N2$ represent the density of atoms in energy levels $E1$ and $E2$, respectively, with $g1$ and $g2$ being the corresponding degeneracy of the levels, K is Boltzmann’s constant and T is the absolute temperature.

As the density of atoms in the lower or ground energy state $E1$ is $N1$, the rate of upward transition or absorptionis proportional to both $N1$ and the spectral density ρf of the radiation energy at the transition frequency f. Hence,the upward transition rate $R12$ may be written as:

$$R12 = N1\rho f\, B12$$

where the constant of proportionality $B12$ is known as the Einstein coefficient of absorption.

For spontaneous emission the average time that an electron exists in the excited state before a transition occursis known as the spontaneous lifetime $\tau 21$. If the density of atoms within the system with energy $E2$ is $N2$, then the spontaneous emission rate is given by the product of $N2$ and $1/\tau 2$. This may be written as $N2A21$ where $A21$,the Einstein coefficient of spontaneous emission, is equal to the reciprocal of the spontaneous lifetime.

The rate of stimulated downward transition of an electron from level 2 to level 1 may be obtained in a similar manner to the rate of stimulated upward transition. Hence the rate of stimulated emission is given by

$$R21 = N2A21 + N2\rho f\, B21$$

For a system in thermal equilibrium, the upward and downward transition rates must be equal and therefore $R12 = \mathrm{R}21$, or:

$$N1\rho f\ B12 = N2A21 + N2\rho fB21$$

It follows that:

$$\rho_f = \frac{N_2 A_{21}}{N_1 B_{12} - N_2 B_{21}}$$

and:

$$\rho_f = \frac{A_{21}/B_{21}}{(B_{12} N_1/B_{21} N_2) - 1}$$

Substituting values from equations

$$\rho_f = \frac{A_{21}/B_{21}}{[(g_1 B_{12}/g_2 B_{21})\ \exp(hf/KT)] - 1}$$

Planck showed thatthe radiation spectral density for a black body radiating within a frequency range *f* to *f* + d*f*isgiven by

$$\rho_f = \frac{8\pi hf^3}{c^3}\left[\frac{1}{\exp(hf/KT) - 1}\right]$$

After comparing equations,

$$B_{12} = \left(\frac{g_2}{g_1}\right) B_{21}$$

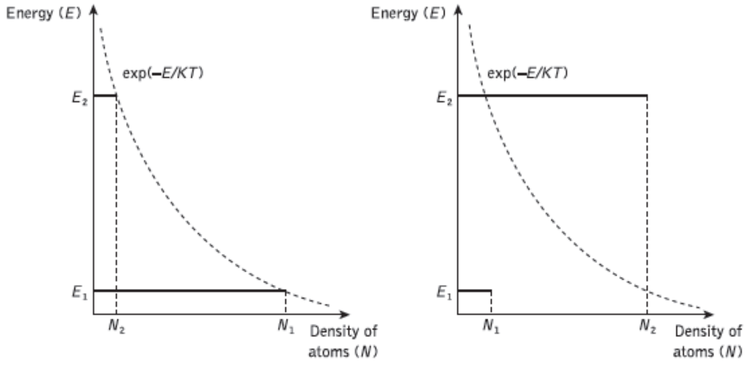
&

$$\frac{A_{21}}{B_{21}} = \frac{8\pi hf^3}{c^3}$$

The ratio of the stimulated emission rate to the spontaneous emission rate is given by:

$$\frac{\text{Stimulated emission rate}}{\text{Spontaneous emission rate}} = \frac{B_{21}\rho_f}{A_{21}} = \frac{1}{\exp(hf/KT) - 1}$$

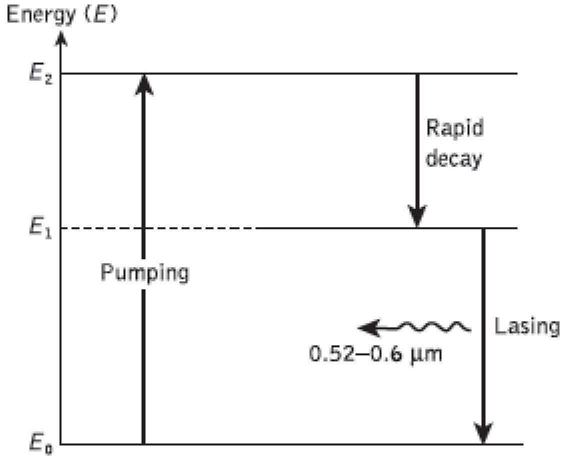
2.1.1 Population inversion

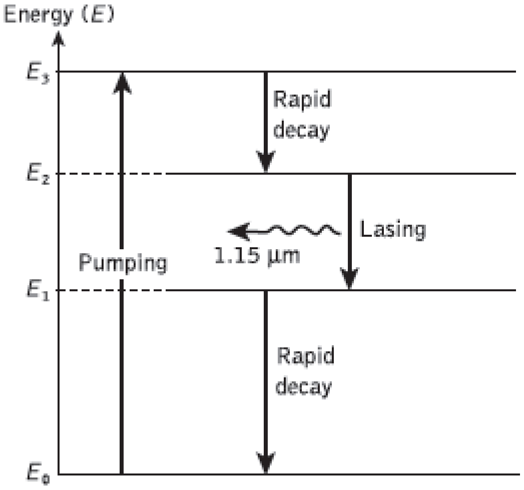


Under the conditions of thermal equilibrium given by the Boltzmann distribution, the lower energy level $E1$ of the two-level atomic system contains more atoms than the upper energy level$E2$, which is normal for structures at room temperature. However, to achieve optical amplification it is necessary to create a non-equilibrium distribution of atoms such that the population of the upper energy level is greater than that of the lower energy level (i.e. $N2 > N1$). This condition is known as population inversion.

In order to achieve population inversion it is necessary to excite atoms into the upper energy level $E2$ and hence obtain a non-equilibrium distribution. This process is achieved using an external energy source and isreferred to as ‘pumping’. When the two levels are equally degenerate (or not degenerate), then $B12 = B21$. Thusthe probabilities of absorption and stimulated emission are equal, providing at best equal populations in the two levels.

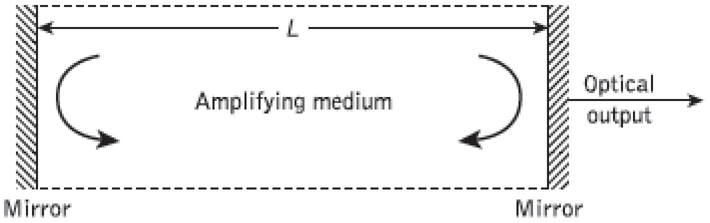
Population inversion may be obtained in systems with three or four energy levels. To achieve population inversion both systems display a central metastable state in which the atoms spend an unusually long time. It isfrom this metastable level that the stimulated emission or lasing takes place.





2.1.1 Optical feedback and laser oscillation

Light amplification in the laser occurs when a photon colliding with an atom in the excited energy state causes the stimulated emission of a second photon and then both these photons release two more. Continuation of this process effectively creates avalanche multiplication, and when the electromagnetic waves associated with these photons are in phase, amplified coherent emission is obtained. To achieve this laser action it is necessary to contain photons within the laser medium and maintain the conditions for coherence. This is accomplished by placing or forming mirrors (plane or curved) at either end of the amplifying medium. The optical cavity formed is more analogous to an oscillator than an amplifier as it provides positive feedback of the photons by reflection at the mirrors at either end of the cavity. Hence the optical signal is fed back many times while receiving amplification as it passes through the medium.



Since the structure forms a resonant cavity, when sufficient population inversion exists in the amplifying medium the radiation builds up and becomes established as standing waves between the mirrors. Thus when the optical spacing between the mirrors is *L*, the resonance condition along the axis of the cavity is given by:

$$L = \frac{\lambda q}{2n}$$

where λ is the emission wavelength, *n* is the refractive index of the amplifying mediumand*q* is an integer. Alternatively, discrete emission frequencies *f* is defined by:

$$f = \frac{qc}{2nL}$$

The different frequencies of oscillation within the laser cavity are determined by the various integer values of *q*
and each constitutes a resonance or mode. These modes are separated by a frequency interval δ*f* where:

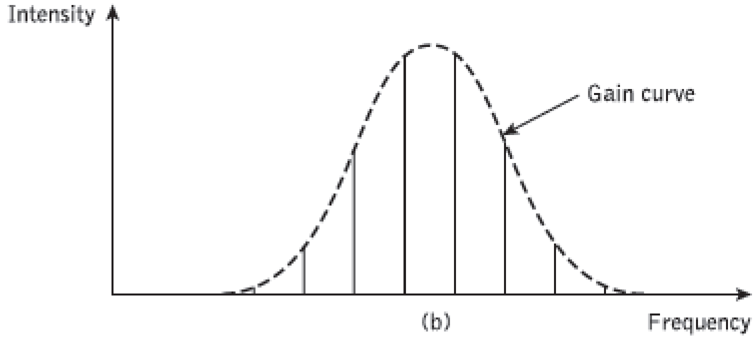
The mode separation in terms of the free space wavelength, assuming δ*f*_ *f* and as*f* = *c*/λ, is given by:

$$\delta\lambda = \frac{\lambda \delta f}{f} = \frac{\lambda^2}{c}\,\delta f$$

Hence,

$$\delta f = \frac{c}{2nL}$$

$$\delta\lambda = \frac{\lambda^2}{2nL}$$



Threshold condition for laser oscillation

The steady-state conditions for laser oscillation are achieved when the gain in the amplifying medium exactly balances the total losses. Hence, although population inversion between the energy levels providing the laser transition is necessary for oscillation to be established, it is not alone sufficient for lasing to occur. We assume the amplifying medium occupies a length *L* completely filling the region between the two mirrors which have reflectivity's *r*1 and *r*2. On each round trip the beam passes through the medium twice. Hence the fractional lossincurred by the light beam is:

$$\text{Fractional loss} = r_1 r_2 \exp(-2AL)$$

It is found that the increase in beam intensity resulting from stimulated emission is exponential

Therefore if the gain coefficient per unit length produced by stimulated emission is C cm−1, the fractionalround trip gain is given by:

$$\text{Fractional gain} = \exp(2CL)$$

$$\text{Hence: } \exp(2CL) \times r_1 r_2 \exp(-2AL) = 1$$

$$\text{And} \quad r_1 r_2 \exp[2(C - A)L] = 1$$

The threshold gain per unit length may be obtained by rearranging the above expression to give:

$$\bar{g}_{\text{th}} = \bar{\alpha} + \frac{1}{2L} \ln \frac{1}{r_1 r_2}$$

The second term on the right-hand side represents the transmission loss through the mirrors.

Laser Diode Rate Equation

The relationship between optical output power and the diode drive current can be determined by examined bythe rate equations that govern the interaction of photons and electrons in the active region. For a p-n junction with a carrier confinement region of depth d, the rate of equation are given by

$=C n\varphi + R_{sp}$-...(1)

= stimulated emission+ spontaneous emission+ photon loss; which governs the number of photons φ and

$=--C n\varphi$.... (2)

= injection+ spontaneous recombination+ stimulated emission; which governs the number of electrons n

Where; C= coefficient describing the strength of
the optical absorptionRsp=rate of
spontaneous emission into lasing mode
τ_{ph}= photon life time
τ_s= spontaneous recombination lifetime

on solving equation 1 and 2 for a steady state condition will yield an expression for the output power.In first equation assuming R_{sp} is negligible and nothing that dφ/dt must be positive is small, we have;

$$\mathbf{C n - 1/\tau_{ph} \geq 0}$$

This shows that n must exceed a threshold value nth in order for φ to increase. So from eq 1, this threshold value can be expressed in terms of the threshold current J_{th} needed to maintain an inversion level $n=n_{th}$ in steadystate when no. Of photons φ=0

This expression defines the current requirement to sustain an excess electron density in the laser whenspontaneous emission is the only decay mechanism,
Now consider the photon and electron rate equations in the steady state condition at the lasing threshold

$$0=Cn_{th}\phi_s+Rsp-\phi_s/\tau_{ph} \qquad (4)$$

$$0=--Cn_{th}\varphi_s\ldots\ldots. (5)$$

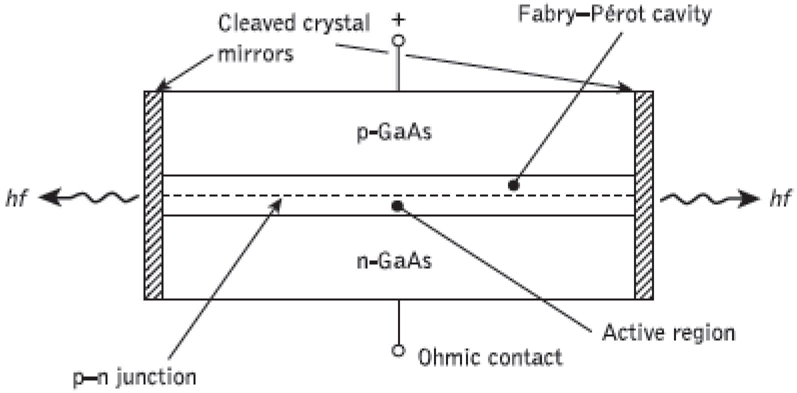
After adding these two equations, the no of photons per unit volume

$$\phi_{s=}(J-J_{th})+\tau_{ph}R_{sp}$$

The Semiconductor Injection Laser

Stimulated emission by the recombination of the injected carriers is encouraged in the semiconductor injectionlaser (also called the injection laser diode (ILD) or simply the injection laser) by the provision of an optical cavity in the crystal structure in order to provide the feedback of photons. This gives the injection laser severalmajor advantages over other semiconductor sources (e.g. LEDs) that may be used for optical communications.These are as follows:

1. High radiance due to the amplifying effect of stimulated emission. Injection lasers will generally supply millwatts of optical output power.
2. Narrow line width on the order of 1 nm (10 Å) or less which is useful in minimizing the effects of materialdispersion.
3. Modulation capabilities which at present extend up into the gigahertz range and will undoubtedly beimproved upon.
4. Relative temporal coherence which is considered essential to allow heterodyne (coherent) detection in high-capacity systems, but at present is primarily of use in single-mode systems.
5. Good spatial coherence which allows the output to be focused by a lens into a spot which has a greaterintensity than the dispersed unfocused emission.



Schematic diagram of a GaAs homojunction injection laser with a Fabry–Pérot

cavity The DH injection laser fabricated from lattice-matched III– V alloys provided both carrier and optical confinement on both sides of the *p*–*n* junction, giving the injection laser a greatly enhanced performance. Thisenabled these devices with the appropriate heat sinking to be operated in a CW mode at 300 K with obvious advantages for optical communications

Efficiency

It is the differential external quantum efficiency which is the ratio of the increase in photon output rate for a given increase in the number of injected electrons. If *P*e is the optical power emitted from the device, *I* is thecurrent, *e* is the charge on an electron and *hf*is the photon energy, then:

$$\eta_D = \frac{dP_e/hf}{dI/e} \simeq \frac{dP_e}{dI(E_g)}$$

Where *E*g is the band gap energy expressed in eV. It may be noted that efficiency gives a measure of the rate ofchange of the optical output power with current and hence defines the slope of the output characteristic. The internal quantum efficiency of the semiconductor laser η_i,

$$\eta_i = \frac{\text{number of photons produced in the laser cavity}}{\text{number of injected electrons}}$$

It is related to the differential external quantum efficiency by the expression

$$\eta_D = \eta_i \left[\frac{1}{1 + (2\bar{\alpha}L/\ln(1/r_1 r_2))} \right]$$

Where A is the loss coefficient of the laser cavity, *L* is the length of the laser cavity and *r*1,*r*2 is the cleavedmirror reflectivity.
Another parameter is the total efficiency (external quantum efficiency) η_T which is efficiency defined as:

$$\eta_T = \frac{\text{total number of output photons}}{\text{total number of injected electrons}}$$

$$= \frac{P_e/hf}{I/e} \simeq \frac{P_e}{IE_g}$$

As the power emitted P_e changes linearly when the injection current *I* is greater than the threshold current *I*th,then:

$$\eta_T \simeq \eta_D \left(1 - \frac{I_{th}}{I} \right)$$

For high injection current (e.g. $I = 5I$th) then $\eta_T \approx \eta_D$, whereas for lower currents ($I \approx 2I$th) the total efficiency islower and around 15 to 25%.
The external power efficiency of the device (or device efficiency) η_{ep} in converting electrical input to opticaloutput is given by:

$$\eta_{ep} = \frac{P_e}{P} \times 100 = \frac{P_e}{IV} \times 100\%$$

For the total efficiency we find:

$$\eta_{ep} = \eta_T \left(\frac{E_g}{V} \right) \times 100\%$$

Stripe geometry

The DH laser structure provides optical confinement in the vertical direction through the refractive index step atthe heterojunction interfaces, but lasing takes place across the whole width of the device.

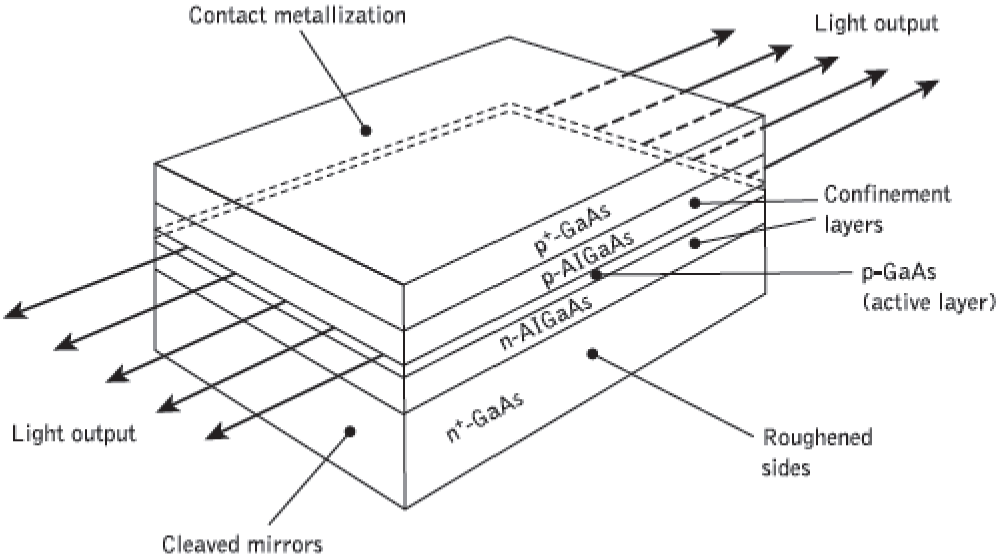


Figure shows the broad-area DH laser where the sides of the cavity are simply formed by roughening the edges of the device in order to reduce unwanted emission in these directions and limit the number of horizontal transverse modes. However, the broad emission area creates several problems including difficult heat sinking, lasing from multiple filaments in the relatively wide active area and unsuitable light output geometry for efficient coupling to the cylindrical fibers.

To overcome these problems while also reducing the required threshold current, laser structures in which the active region does not extend to the edges of the device were developed. A common technique involved the introduction of stripe geometry to the structure to provide optical containment in the horizontal plane.

External quantum efficiency g_{th}

The external quantum efficiency η_{ext} is defined as the number of photons emitted per radiative electron – holepair recombination above threshold.

Experimentally, $\eta_{ext}$is calculated from the straight-line portion of the curve for the emitted optical power P versusdrive current I, which gives

$$\eta_{ext} == 0.806\ \lambda$$

Fiber Splicing:

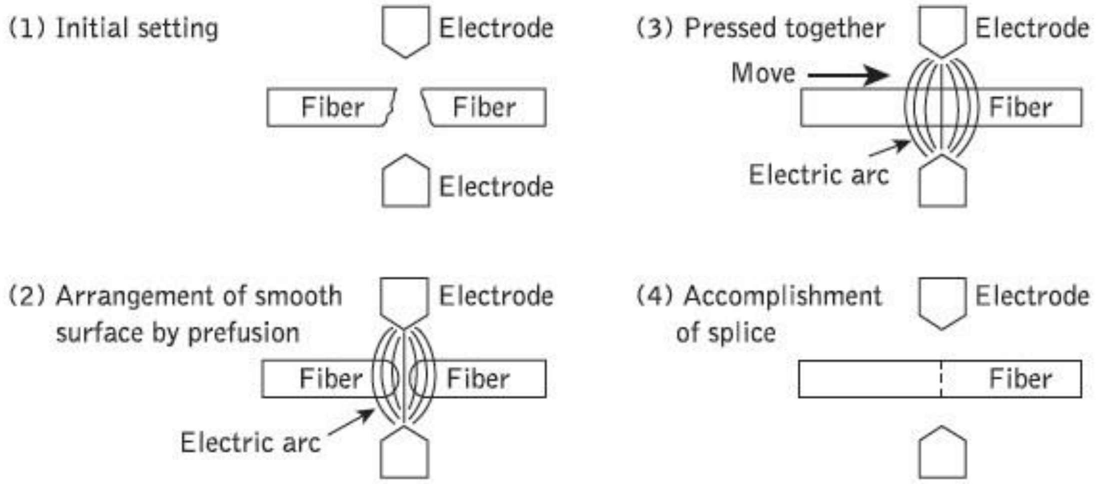
A permanent joint formed between two individual optical fibers in the field or factory is known as a fiber splice.Fiber splicing is frequently used to establish long-haul optical fiber links where smaller fiber lengths need to be joined, and there is no requirement for repeated connection and disconnection. Splices may be divided into two broad categories depending upon the splicing technique

1) **Fusion splicing or welding:** Fusion splicing is accomplished by applying localized heating (e.g. by a flame or an electric arc) at the interface between two butted, pre-aligned fiber ends causing them to soften and fuse.

   Mechanical splicing: Mechanical splicing, in which the fibers are held in alignment by some mechanical means, may be achieved by various methods including the use of tubes around the fiber ends (tube splices) or V-groovesinto which the butted fibers are placed.

Fusion splicing

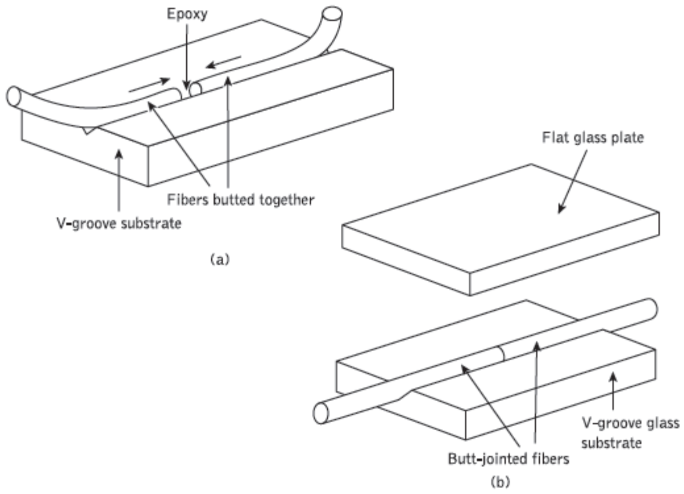
Fusion splicing is the act of joining two optical fibers end-to-end using heat. The goal is to fuse the two fibers together in such a way that light passing through the fibers is not scattered or reflected back by the splice, and so that the splice and the region surrounding it are almost as strong as the virgin fiber itself. The source of heatis usually an electric arc, but can also be a laser, or a gas flame, or a tungsten filament through which current is passed.



Fusion splicing of single-mode fibers with typical core diameters between 5 and 10 μm presents problems of more critical fiber alignment (i.e. lateral offsets of less than 1 μm are required for low-loss joints). However, splice insertion losses below 0.3 dB may be achieved due to a self-alignment phenomenon which partially compensates for any lateral offset.

Mechanical splicing

The most common mechanical splicing technique is V-groove method. V-groove splices formed by sandwiching the butted fiber ends between a V-groove glass substrate and a flat glass retainer plate have also proved very successful in the laboratory. Splice insertion losses of less than 0.01 dB when coupling single-modefibers have been reported using this technique.



Fiber connectors

ptical fiber connectors are used to join optical fibers where a connect/disconnect capability is required. This is because they must maintain similar tolerance requirements to splices in order to couple light between fibers efficiently, but they must accomplish it in a removable fashion.

Hence optical fiber connectors may be considered in three major areas, which are:

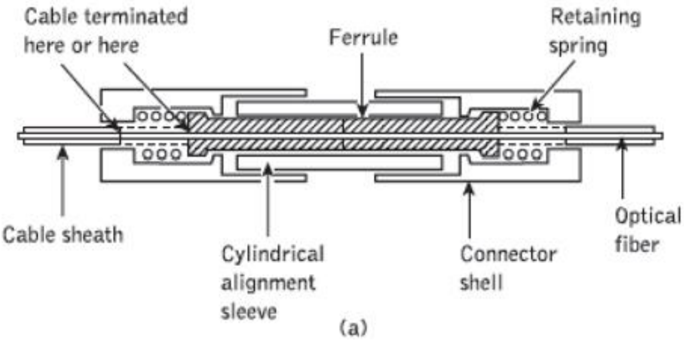
(a) the fiber termination, which protects and locates the fiber ends;

(b) the fiber end alignment to provide optimum optical coupling;

(c) The outer shell, which maintains the connection and the fiber alignment, protects the fiber ends from theenvironment and provides adequate strength at the joint.

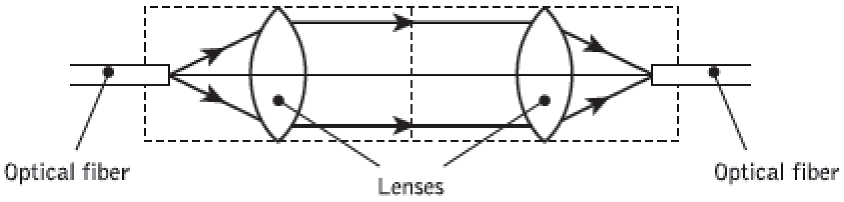
Cylindrical ferrule connectors

The basic ferrule connector which is perhaps the simplest optical fiber connector design, is illustrated in Figure: The two fibers to be connected are permanently bonded (with epoxy resin) in metal plugs known as ferrules which have an accurately drilled central hole in their end faces where the stripped (of buffer coating) fiber is located. Within the connector the two ferrules are placed in an alignment sleeve which, using accurately machined components, allows the fiber ends to be butt jointed.



Expanded beam connectors

An alternative to connection via direct butt joints between optical fibers is offered by the principle of the expanded beam. It shows a connector consisting of two lenses for collimating and refocusing the light from one fiber into the other. The use of this interposed optics makes the achievement of lateral alignment much less critical than with a butt-jointed fiber connector. Expanded beam connectors are useful for multi-fiber connection and edge connection for printed circuit boards where lateral and longitudinal alignment are frequently difficult to achieve



Fiber couplers

An optical fiber coupler is a device that distributes light from a main fiber into one or more branch fibers. The latter case is more normal and such devices are known as multiport fiber couplers. Requirements are increasing for the use of these devices to divide or combine optical signals for application within optical fiber information distribution systems including data buses, LANs, computer networks and telecommunication access networks. Optical fiber couplers are often passive devices in which the power transfer takes place either:

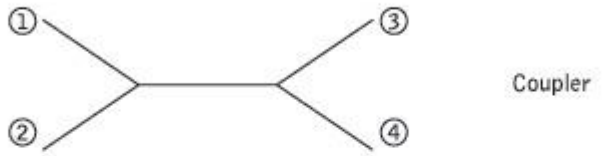
(a) Through the fiber core cross-section by butt jointing the fibers or by using some form of imaging opticsbetween the fibers (core interaction type); or

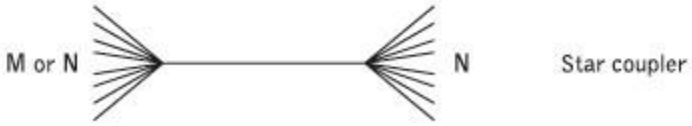
(b) Through the fiber surface and normal to its axis by converting the guided core modes to both cladding andrefracted modes which then enable the power-sharing mechanism.

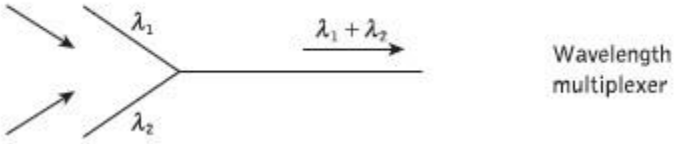
Multiport optical fiber couplers can also be subdivided into the following three main groups

1. Three- and four-port couplers, which are used for signal splitting, distribution and combining.
2. Star couplers, which are generally used for distributing a single input signal to multiple outputs.
3. Wavelength division multiplexing (WDM) devices, which are a specialized form of coupler designed topermit a number of different peak wavelength optical signals to be transmitted in parallel on a single fiber.

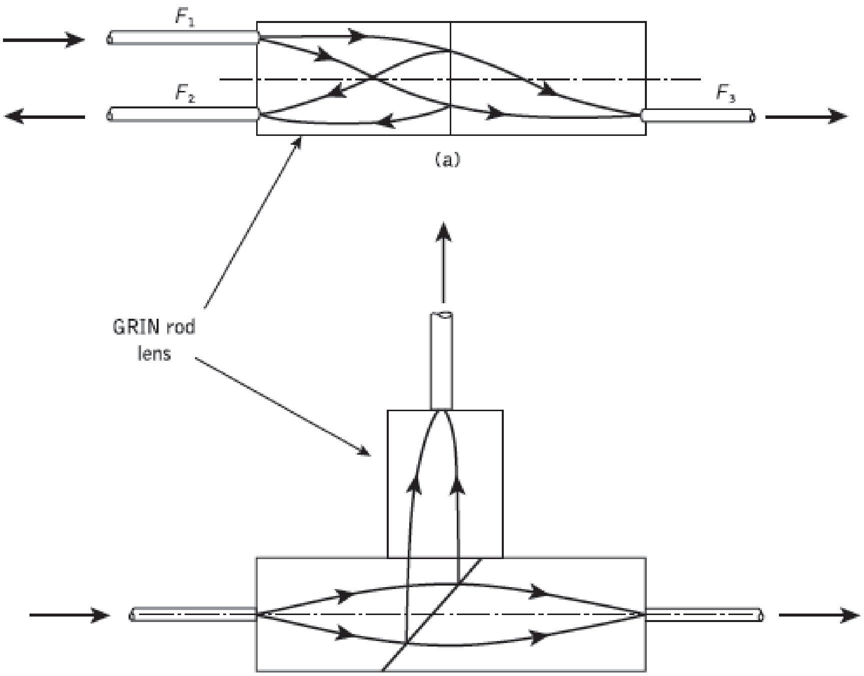
Ideal fiber couplers should distribute light among the branch fibers with no scattering loss or the generation of noise, and they should function with complete insensitivity to factors including the distribution of light between the fiber modes, as well as the state of polarization of the light.



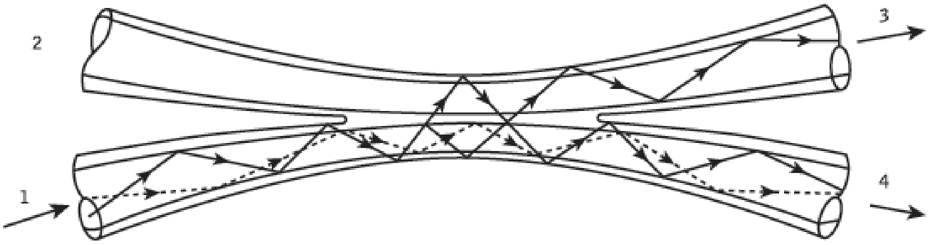




Three- and four-port couplers



s three port coupler r in between. Light cident on the mirror. A portion of the incident beam is reflected back and is coupled to fiber *F*2, while the transmitted light is focused in the second lens and then coupled to fiber *F*3.



The various loss parameters associated with four-port couplers may be written down with reference to Figure.Hence, the excess loss which is defined as the ratio of power input to power output is given by:

$$\text{Excess loss (four-port coupler)} = 10\log_{10}\frac{P_1}{(P_3+P_4)}\ \text{(dB)}$$

The insertion loss, however, is generally defined as the loss obtained for a particular port-to-port optical path

$$\text{Insertion loss (ports 1 to 4)} = 10\log_{10}\frac{P_1}{P_4}\ \text{(dB)}$$

$$\text{Crosstalk (four-port coupler)} = 10\log_{10}\frac{P_2}{P_1}\ \text{(dB)}$$

$$\text{Split ratio} = \left[\frac{P_3}{(P_3+P_4)}\right]\times 100\%$$

$$= \left[1-\frac{P_4}{(P_3+P_4)}\right]\times 100\%$$

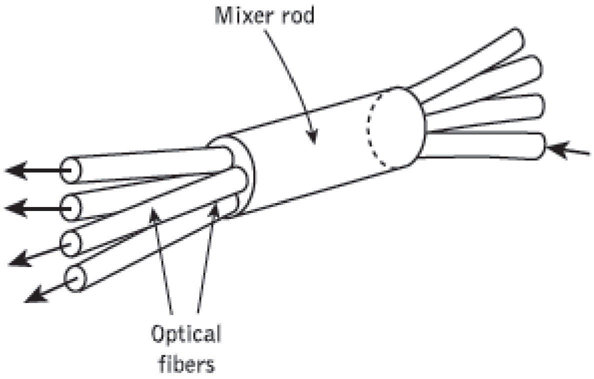
Star couplers

In an ideal star coupler the optical power from any input fiber is evenly distributed among the output fibers. Thetotal loss associated with the star coupler comprises its theoretical splitting loss together with the excess loss.
The splitting loss is related to the number of output ports *N* following:

Splitting loss (star coupler) = 10 log10 *N* (dB)

For a single input port and multiple output ports where *j* = 1, *N*, then the excess loss is given by:

$$\text{Excess loss (star coupler)} = 10\log_{10}\left(P_i\Big/\sum_{1}^{N}P_j\right)\ \text{(dB)}$$



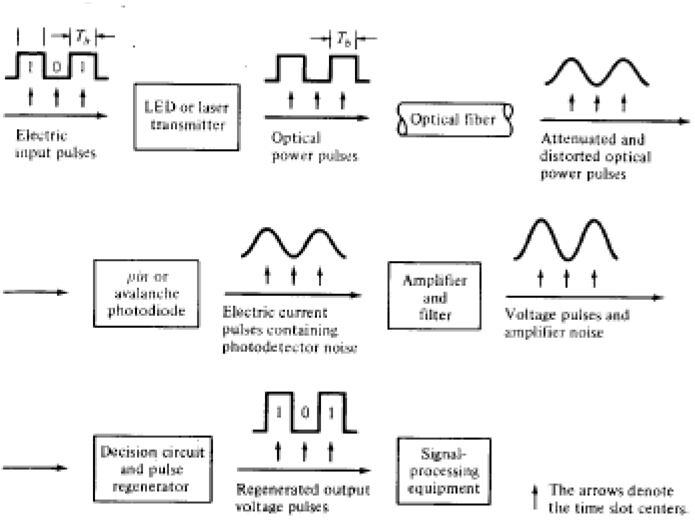
UNIT IV FIBER OPTIC RECEIVER AND MEASUREMENTS

- Fundamental receiver operation
- Pre-amplifiers
- Error sources
- Receiver Configuration
- Probability of Error
- Quantum limit
- Fiber Attenuation measurements
- Dispersion measurements
- Fiber Refractive index profile measurements
- Fiber cut- off Wave length Measurements
- Fiber Numerical Aperture Measurements
- Fiber diameter measurements

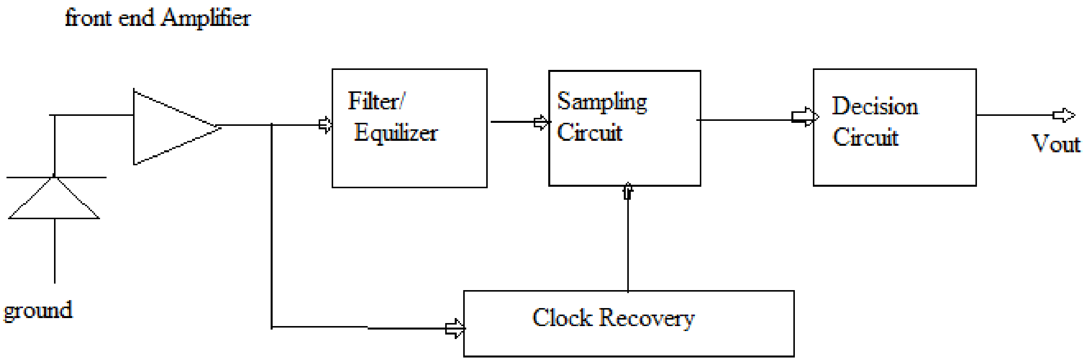
OPTICAL RECEIVER OPERATION:

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 version of this distorted signal.

DIGITAL SIGNAL TRANSMISSION:



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

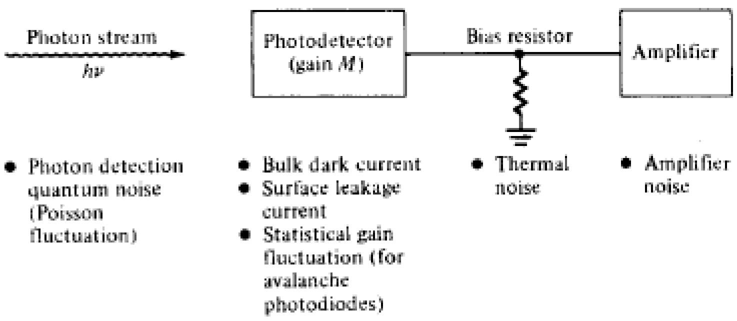


As per the diagram, the first element is either a pin or an avalanche photodiode, which produces an electric current that is proportional to the received power level. Since this electric current is typically very weak, a front end amplifier boosts it to a level that can be used by the following electronics.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

$$N= \frac{y}{h\nu}\int_0^{\tau} P(t)dt = \frac{yE}{h\nu}$$

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:

$$\underset{r}{P}\,(n) \underset{\to}{=} \frac{N^{n}}{y!}$$

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)

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).

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

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

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

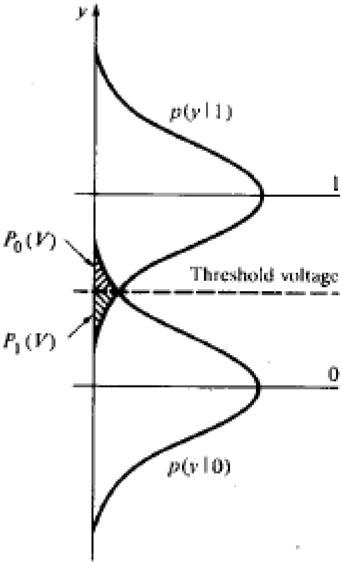
$$P_1(v) = \int_{-\infty}^{v} P(y/1)dy \qquad (1)$$

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

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

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

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



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.

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

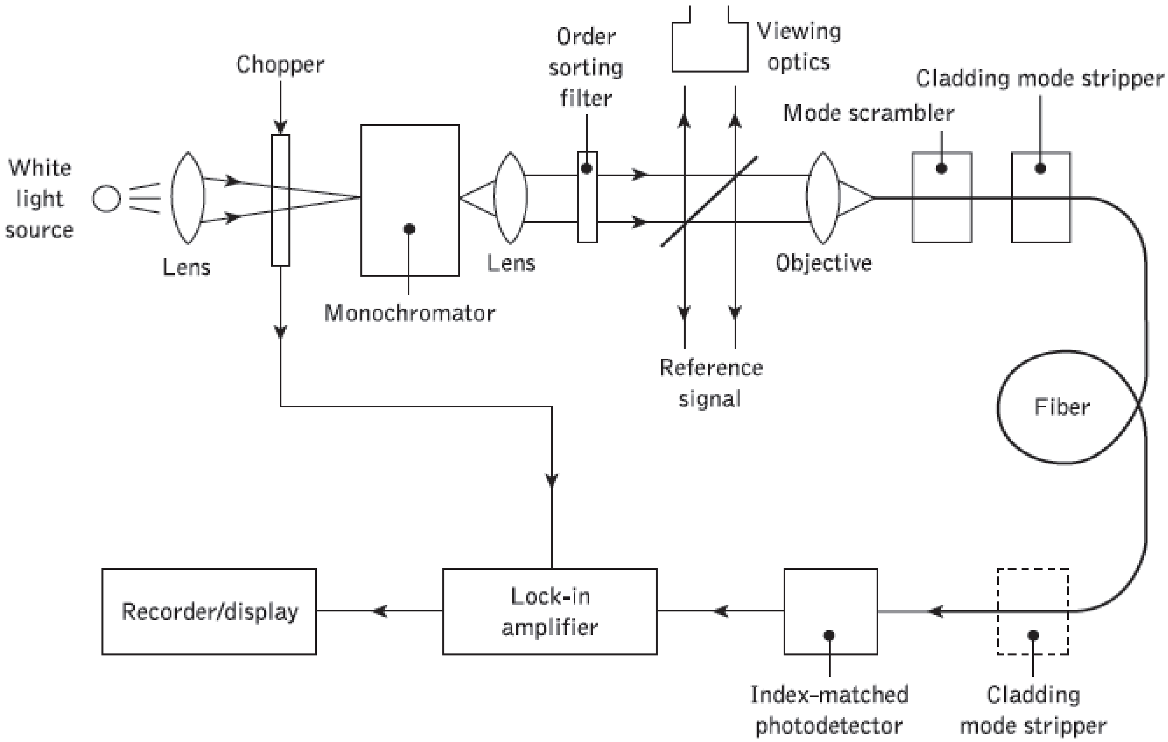
OPTICAL FIBER MEASUREMENTS

- Three main areas:
- Transmission characteristics
- Geometrical and optical characteristics
- Mechanical characteristics

STANDARD MEASUREMENT TECHNIQUES

- **Reference Test Method** :where measurement of characteristic is strictly done according to definitions which gives highest degree of accuracy and reproducibility
- **Alternate Test Method** :where measurement is done deviating from strict definitions which is suitable for practical use.

FIBER ATTENUATION MEASUREMENT



- Fiber attenuation also called as transmission loss.
- Attenuation = optical power input/optical power at the fiber end
- $= (10/L)\log(P_i/P_o)$ dB/km
- L – length of the fiber
- A commonly used technique for determining the total fiber attenuation per unit length is the cut-back or differential method.
- The above Figure shows a schematic diagram of the typical experimental setup for measurement of the spectral loss to obtain the overall attenuation spectrum for the fiber.

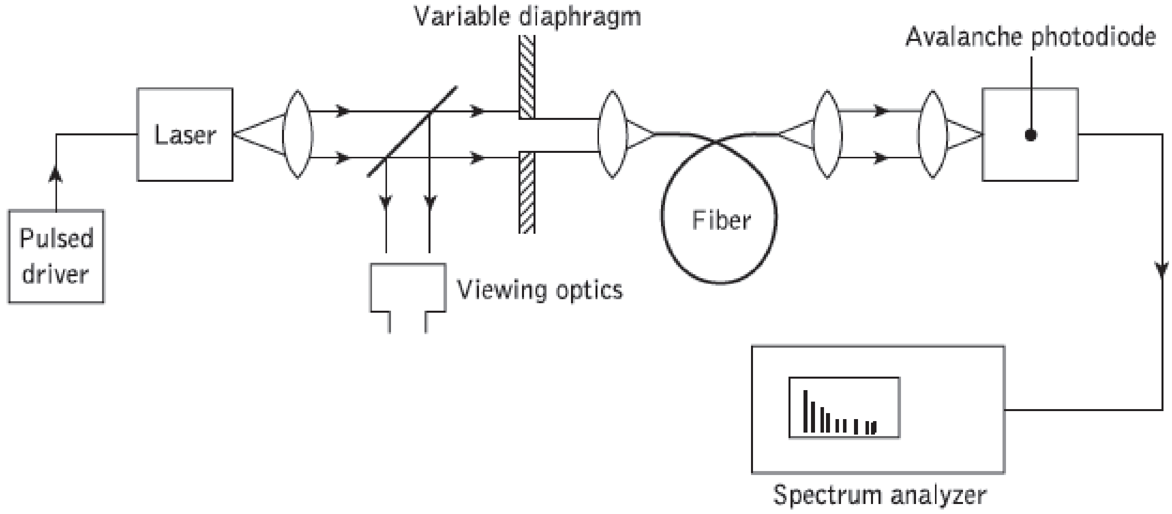
- It consists of a ‘white’ light source, usually a tungsten halogen or xenon arc lamp.
- The focused light is mechanically chopped at a low frequency of a few hundred hertz.
- This enables the lock-in amplifier at the receiver to perform phase-sensitive detection.
- The chopped light is then fed through a monochromator which utilizes a prism or diffraction grating arrangement to select the required wavelength at which the attenuation is to be measured.
- Hence the light is filtered before being focused onto the fiber by means of a microscope objective lens.
- A beam splitter may be incorporated before the fiber to provide light for viewing optics and a reference signal used to compensate for out- put power fluctuations.
- The measurement is performed on multimode fibers it is very dependent on the optical launch conditions.
- Therefore unless the launch optics are arranged to give the steady-state mode distribution at the fiber input, or a dummy fiber is used, then a mode scrambling device is attached to the fiber within the first meter.
- The fiber is also usually put through a cladding mode stripper, which may consist of an S-shaped groove cut in the Teflon and filled with glycerine.
- This device removes light launched into the fiber cladding through radiation into the index-matched (or slightly higher refractive index) glycerine.
- A mode stripper can also be included at the fiber output end to remove any optical power which is scattered from the core into the cladding down the fiber length.
- This tends to be pronounced when the fiber cladding consists of a low-refractive-index silicone resin.
- The optical power at the receiving end of the fiber is detected using a p–i–n or avalanche photodiode.
- In order to obtain reproducible results the photodetector surface is usually index matched to the fiber output end face using epoxy resin or an index-matching gell .
- Finally, the electrical output from the photodetector is fed to a lock-in amplifier, the output of which is recorded.
- The cut-back method involves taking a set of optical output power measurements over the required spectrum using a long length of fiber (usually at least a kilometer).
- $\alpha_{dB} =(10/L_1-L_2)\log_{10}V_2/V_1$
- Where $V_1$and V_2correspond to output voltage readings from the cut-back fiber length respectively.
- The electrical voltage substituted for the optical powers $P_{01}$and P_{02} of above Eq. as to these optical powers.

- The accuracy of using this method is largely dependent on constant optical achievement of the equilibrium mode distribution within the fiber to detector power coupling changes between measureme made less than 0.01dB .
- Hence the cut-back technic for attenuation measurements by the EIA as well as the ITU.

FIBER DISPERSION MEASUREMENT

- Dispersion measurements give an indication of the distortion to optical signals.
- Delay distortion leads to broadening of transmitted light pulses limits the information carrying capacity of fiber.
- Three major mechanisms which produce dispersion in optical fibers are material, waveguide and intermodal dispersion.
- In multimode fibers intermodal dispersion tends to be dominant mechanisms, in single mode fibers intermodal dispersion is non existent as only a single mode is allowed to propagate.
- Dispersion measurement is of two types
- Frequency domain measurement.
- Time domain measurement

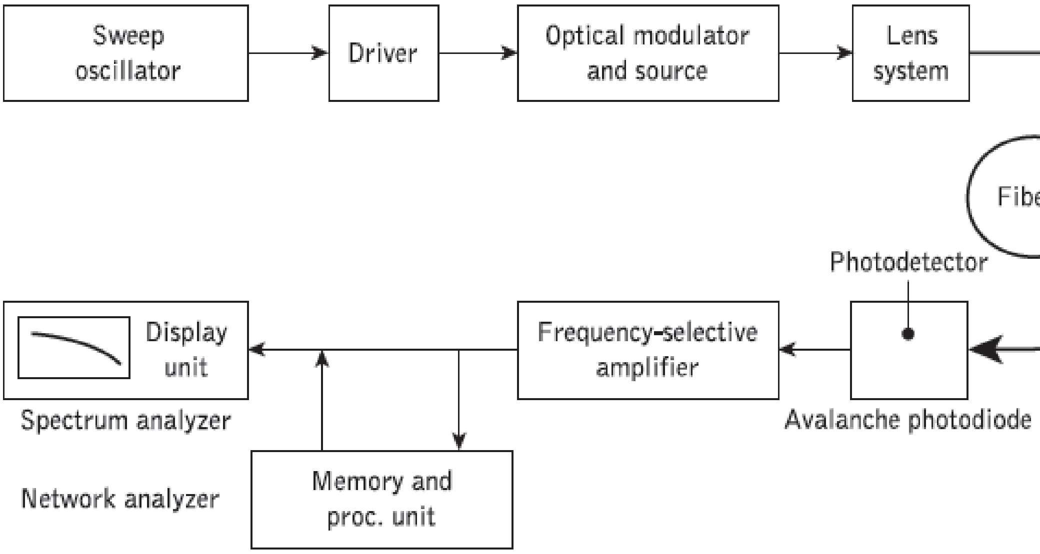
FREQUENCY DOMAIN MEASUREMENT



Experimental setup for making fiber dispersion measurements in the frequency domain using a pulsed laser source

- Frequency domain measurement is preferred method for obtaining baseband frequency and bandwidth of multimode optical fibers.
- The sampling oscilloscope is replaced by a spectrum analyser which takes the fourier transform of the pulse in the time domain and hence display its frequency components

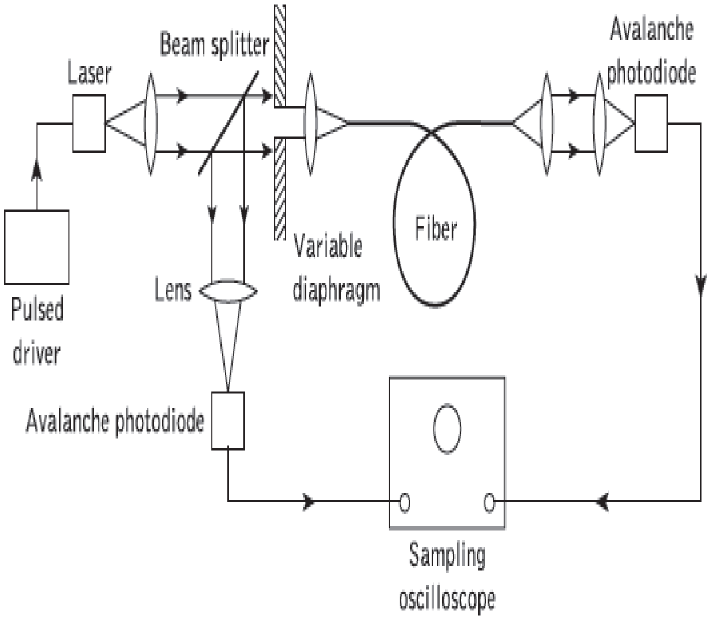
SWEPT FREQUENCY MEASUREMENT METHOD



Block schematic showing an experimental arrangement for the swept frequency measurement method to provide fiber dispersion measurements in the frequency domain

- The signal energy is very narrow frequency band in the baseband region unlike the pulse measurement method where the signal energy is spread over the entire baseband region.
- A Optical source is an injection laser which may be directly modulated from sweep oscillator.
- A spectrum analyser may be used in order to obtain a continuous display of the swept frequency signal.
- Network analyser can be employed to give phase and frequency information.
- An electrical or optical reference channel is connected between the oscillator and the meter.
- When an optical signal which is sinusoidally modulated in power with frequency f_m is transmitted through single mode fiber length .
- A delay of one modulation period T_m of $1/f_m$ corresponds to a phase shift of 2π then the sinusoidal modulation is phase shifted in the fiber by an angle θ_m .
- The specific group delay = $\theta_m / 2\pi f_m L$

Time domain measurement of fiber dispersion



- The most common method for time domain measurement of pulse dispersion in multimode optical fibers is illustrated with Short optical pulses (100 to 400 ps) are launched into the fiber from a suitable source (e.g. A1GaAs injection laser) using fast driving electronics.
- The pulses travel down the length of fiber under test (around 1 km) and are broadened due to the various dispersion mechanisms.
- Using a laser with a narrow spectral width when testing a multimode fiber.
- The chromatic dispersion is negligible and the measurement reflects only intermodal dispersion.
- The pulses are received by a high-speed photodetector (i.e. avalanche photodiode) and are displayed on a fast sampling oscilloscope.
- A beam splitter is utilized for triggering the oscilloscope and for input pulse measurement.
- After the initial measurement of output pulse width, the long fiber length may be cut back to a short length and the measurement repeated in order to obtain the effective input pulse width.
- The fiber is generally cut back to the lesser of 10 m or 1% of its original length.
- As an alternative to this cut-back technique, the insertion or substitution method similar to that used in fiber loss measurement can be employed.
- This method has the benefit of being nondestructive and only slightly less accurate than the cut-back technique.

- The fiber dispersion is obtained from the two pulse width measurements which are taken at any convenient fraction of their amplitude.
- The considerations of dispersion are normally made on pulses using the half maximum amplitude or 3 dB points.

$$\tau_o^2(3\text{ dB}) = \tau^2(3\text{ dB}) + \tau_i^2(3\text{ dB})$$

- where τ(3 dB) and τ_i(3 dB) are the 3 dB pulse widths at the fiber input and output, respectively, and τ (3 dB) is the width of the fiber impulse response again measured at half the maximum amplitude.
- Hence the pulse dispersion in the fiber (commonly referred to as the pulse broadening when considering the 3 dB pulse width) in ns km^{-1} is given by

$$\tau(3\text{ dB}) = \frac{(\tau_o^2(3\text{ dB}) - \tau_i^2(3\text{ dB}))^{\frac{1}{2}}}{L}\text{ ns km}^{-1}$$

- where τ(3 dB), τ_i(3 dB) and τ_o(3 dB) are measured in ns and L is the fiber length in km.
- If a long length of fiber is cut back to a short length in order to take the input pulse width measurement, then L corresponds to the difference between the two fiber lengths in km.
- When the launched optical pulses and the fiber impulse response are Gaussian, the 3 dB optical bandwidth for the fiber *B*opt may be calculated using

$$\begin{aligned} B_{\text{opt}} \times \tau(3\text{ dB}) &= 0.44\text{ GHz ns} \\ &= 0.44\text{ MHz ps} \end{aligned}$$

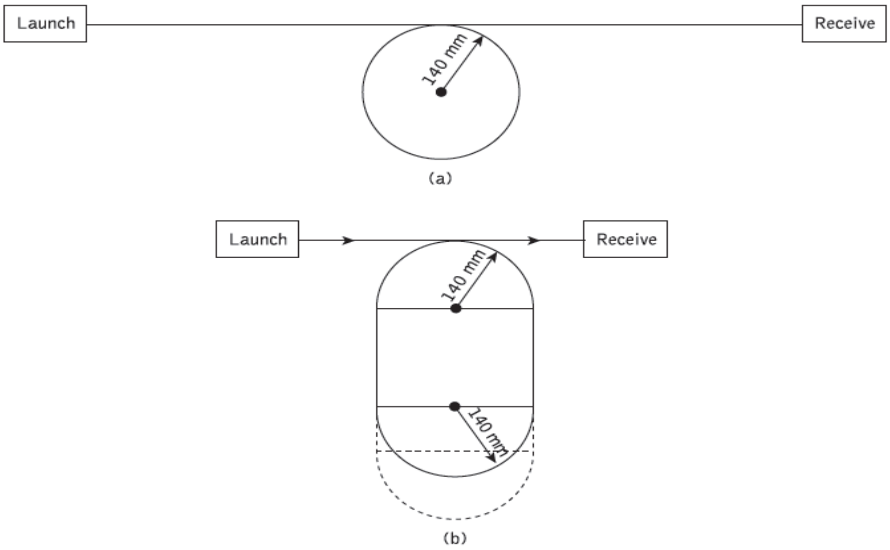
Fiber cutoff wavelength measurements

- A multimode fiber has many cutoff wavelengths because the number of bound propagating modes is usually large.
- For example, considering a parabolic refractive index graded fiber, following equation the number of guided modes M_g is

$$M_g = \left(\frac{\pi a}{\lambda}\right)^2 (n_1^2 - n_2^2)$$

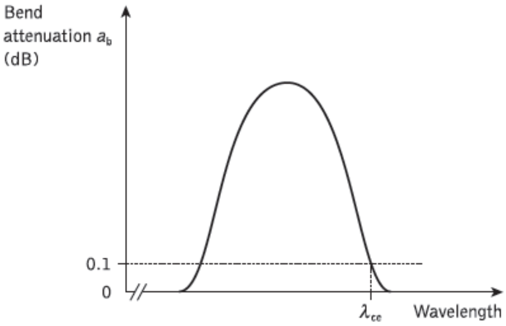
- where a is the core radius and n_1 and n_2 are the core peak and cladding indices respectively.
- The cutoff wavelength of the LP_{11} is the shortest wavelength above which the fiber exhibits single-mode operation and it is therefore an important parameter to measure.
- Because of the large attenuation of the LP_{11} mode near cutoff, the parameter which is experimentally determined is called the effective cutoff wavelength, which is always smaller than the theoretical cutoff wavelength by as much as 100 to 200 nm.

- It is this effective cutoff wavelength which limits the wavelength region for which the fiber is ‘effectively’ single-mode.
- The effective cutoff wavelength is normally measured by increasing the signal wavelength in a fixed length of fiber until the LP_{11} mode is undetectable.
- Since the attenuation of the LP_{11} mode is dependent on the fiber length and its radius of curvature, the effective cutoff wavelength tends to vary with the method of measurement
- The other test apparatus is the same as that employed for the measurement of fiber attenuation by the cut-back method.
- The launch conditions used must be sufficient to excite both the fundamental and the LP_{11} modes, and it is important that cladding modes are stripped from the fiber.
- In the bending-reference technique the power $P_s(\lambda)$ transmitted through the fiber sample in the configurations shown in figure is measured as a function of wavelength.
- Thus the quantity $P_s(\lambda)$ corresponds to the total power, including launched higher order modes, of the cutoff wavelength.



- Then keeping the launch conditions fixed, at least one additional loop of sufficiently small radius (60 mm or less) is introduced into the test sample to act as a mode filter to suppress the secondary LP_{11} mode without attenuating the fundamental mode at the effective cutoff wavelength.
- The smaller transmitted spectral power $P_b(\lambda)$ is measured which corresponds to the fundamental mode power referred to in the definition.
- The bend attenuation $a_b(\lambda)$ comprising the level difference between the total power and the fundamental power is calculated as:
- $a_b(\lambda)=10\log_{10}(P_s(\lambda)/P_b(\lambda))$

- The bend attenuation characteristic exhibits a peak in the wavelength region where the radiation losses resulting from the small loop are much higher for the LP_{11} mode than for the LP_{01} fundamental mode, as illustrated in following figure.



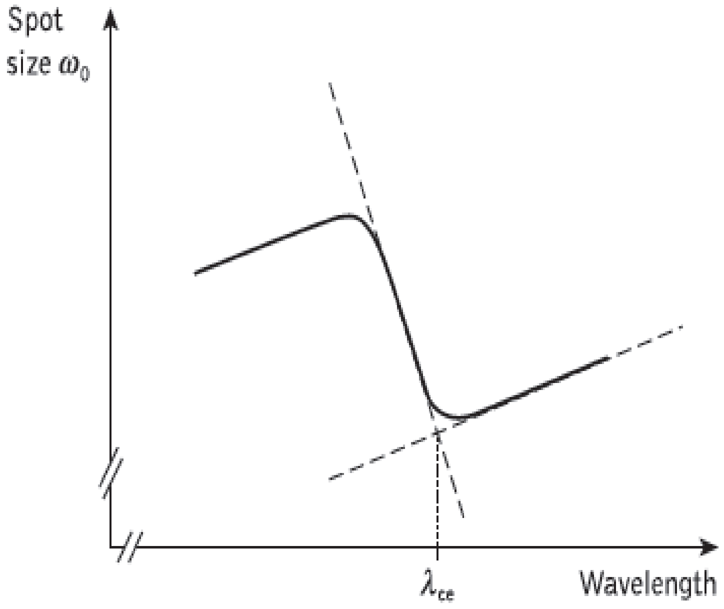
- It should be noted that the shorter wavelength side of the attenuation maximum corresponds to the LP_{11} mode, being well confined in the fiber core, and hence negligible loss is induced by the 60 mm diameter loop, whereas on the longer wavelength side the LP_{11} mode is not guided in the fiber and therefore, assuming that the loop diameter is large enough to avoid any curvature loss to the fundamental mode, there is also no increase in loss.
- The effective cutoff wavelength λ_{ce} it may be determined as the longest wavelength at which the bend attenuation or level difference $a_b(\lambda)$ equals 0.1 dB, as shown in following figure .

POWER STEP TECHNIQUE

- The 2m length of single-mode fiber is replaced by a short (1 to 2 m) length of multimode fiber and the spectral power $P_m(\lambda)$ emerging from the end of the multimode fiber is measured.
- The relative attenuation $a_m(\lambda)$ or level difference between the powers launched into the multimode and single-mode fibers may be computed as:
- $a_m(\lambda)=10\log_{10}(P_s(\lambda)/P_m(\lambda))$

SPOT SIZE

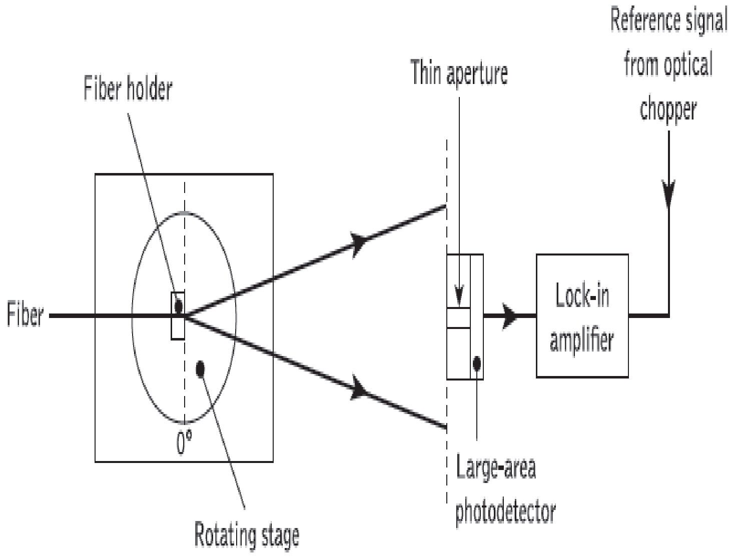
- A third method for determination of the effective cutoff wavelength is the measurement of the change in spot size with wavelength.
- The spot size is measured as a function of wavelength by the transverse offset method using a 2m length of fiber on each side of the joint with a single loop of radius 140 mm formed in each 2m length.
- When the fiber is operating in the single-mode region, the spot size increases almost linearly with increasing wavelength as may be observed in following figure.



Fiber numerical aperture measurements

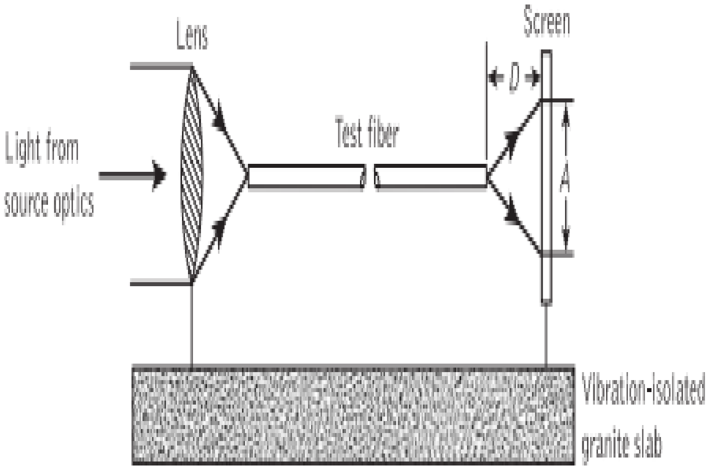
- The numerical aperture is an important optical fiber parameter as it affects characteristics such as the light-gathering efficiency and the normalized frequency of the fiber (*V*).
- This in turn dictates the number of modes propagating within the fiber (also defining the single mode region) which has consequent effects on both the fiber dispersion (i.e. intermodal) and possibly, the fiber attenuation (i.e. differential attenuation of modes).
- The numerical aperture (*NA*) is defined for a step index fiber in air given by
- $NA=\sin\theta_a= (n_1^2-n_2^2)^{1/2}$
- where θ_a is the maximum acceptance angle, n_1 is the core refractive index and n_2 is the cladding refractive index.
- It is assumed in that the light is incident on the fiber end face from air with a refractive index (n_0) of unity.
- numerical aperture thus defined represents only the local *NA* of the fiber on its core axis (the numerical aperture for light incident at the fiber core axis).
- The graded profile creates a multitude of local *NA*s as the refractive index changes radially from the core axis.
- For the general case of a graded index fiber these local numerical apertures *NA*(*r*) at different radial distances *r* from the core axis may be defined by:
- $NA (r) = \sin\theta_a(r)= (n_1^2 (r)-n_2^2)^{1/2}$
- Therefore, calculations of numerical aperture from refractive index data are likely to be less accurate for graded index fibers than for step index fibers unless the complete refractive index profile is considered.

- However, if refractive index data is available on either fiber type from the measurements described the numerical aperture may be determined by calculation.
- Alternatively, a simple commonly used technique for the determination of the fiber numerical aperture is involves measurement of the far-field radiation pattern from the fiber.
- This measurement may be performed by directly measuring the far-field angle from the fiber using a rotating stage, or by calculating the far-field angle using trigonometry.
- An example of an experimental arrangement with a rotating stage is shown in figure.
- A 2m length of the graded index fiber has its faces prepared in order to ensure square smooth terminations.
- The fiber output end is then positioned on the rotating stage with its end face parallel to the plane of the photodetector input, and so that its output is perpendicular to the axis of rotation.
- Light at a wavelength of 0.85 μm is launched into the fiber at all possible angles (overfilling the fiber) using an optical system similar to that used in the spot attenuation measurements



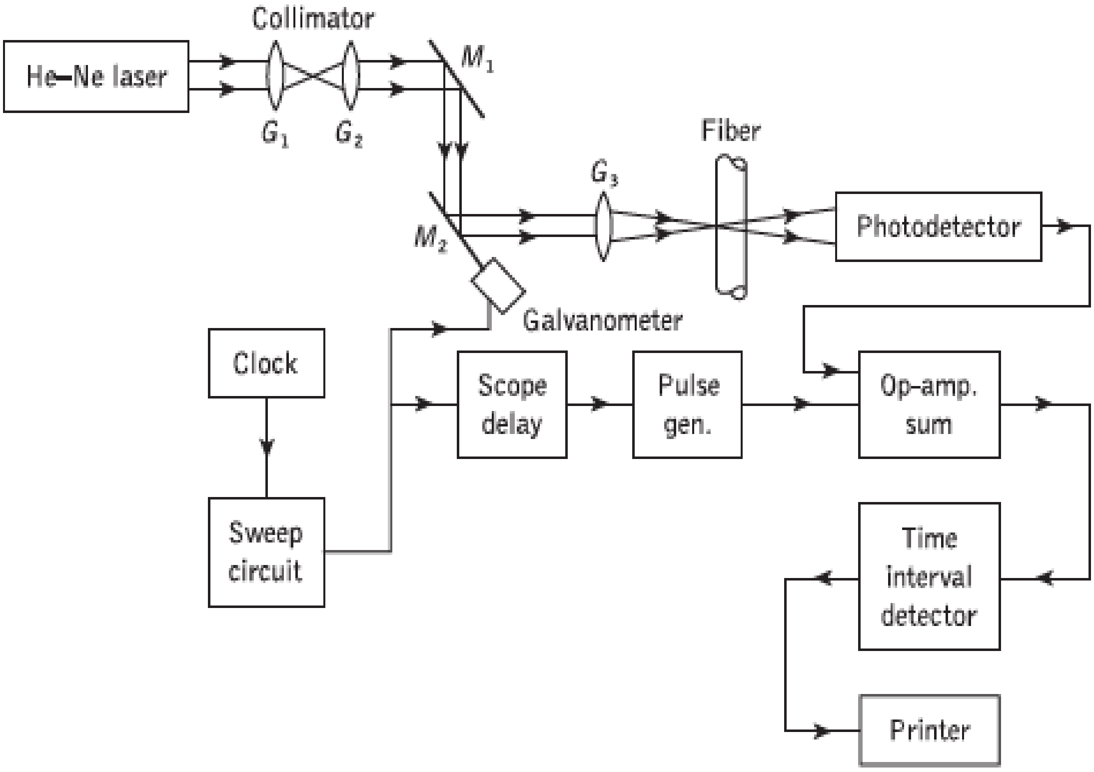
- The photodetector, which may be either a small-area device or an apertured large-area device, is placed 10 to 20 cm from the fiber and positioned in order to obtain a maximum signal with no rotation (0°).
- Hence when the rotating stage is turned the limits of the far-field pattern may be recorded.
- The output power is monitored and plotted as a function of angle, the maximum acceptance angle being obtained when the power drops to 5% of the maximum intensity.

- Thus the numerical aperture of the fiber can be obtained from Eq. This far-field scanning measurement may also be performed with the photodetector located on a rotational stage and the fiber positioned at the center of rotation.
- A less precise measurement of the numerical aperture can be obtained from the far-field pattern by trigonometric means. The experimental apparatus is shown in following figure.



- where the end prepared fiber is located on an optical base plate or slab. Again light is launched into the fiber under test over the full range of its numerical aperture, and the far-field pattern from the fiber is displayed on a screen which is positioned a known distance *D* from the fiber output end face
- The test fiber is then aligned so that the optical intensity on the screen is maximized.
- Finally, the pattern size on the screen *A* is measured using a calibrated vernier caliper.
- The numerical aperture can be obtained from simple trigonometrical relationships where:
- $NA = \sin\theta_a = (A/2) / [(A/2)^2 + D^2]^{1/2} = A / (A^2 + 4D^2)^{1/2}$

Fiber diameter measurements



- **Outer diameter**
- It is essential during the fiber manufacturing process (at the fiber drawing stage) that the fiber outer diameter (cladding diameter) is maintained constant to within 1%.
- Any diameter variations may cause excessive radiation losses and make accurate fiber–fiber connection difficult.
- Hence on-line diameter measurement systems are required which provide accuracy better than 0.3% at a measurement rate greater than 100 Hz (i.e. a typical fiber drawing velocity is 1 m s^{-1}).
- Use is therefore made of noncontacting optical methods such as fiber image projection and scattering pattern analysis.
- The most common on-line measurement technique uses fiber image projection (shadow method) and is illustrated in following Figure.
- In this method a laser beam is swept at a constant velocity transversely across the fiber and a measurement is made of the time interval during which the fiber intercepts the beam and casts a shadow on a photodetector.
- In the apparatus shown in Figure the beam from a laser operating at a wavelength of 0.6328 μm is collimated using two lenses (G1 and G2).
- It is then reflected off two mirrors (M1 and M2), the second of which (M2) is driven by a galvanometer which makes it rotate through a small angle at a constant angular velocity before returning to its original starting position.

- Therefore, the laser beam which is focused in the plane of the fiber by a lens (G3) is swept across the fiber by the oscillating mirror, and is incident on the photodetector unless it is blocked by the fiber.
- The velocity ds/dt of the fiber shadow thus created at the photodetector is directly proportional to the mirror velocity dφ/dt following
- The shadow method for the on-line measurement of the fiber outer diameter

$$\frac{ds}{dt} = l\frac{d\phi}{dt}$$

- where l is the distance between the mirror and the photodetector. Furthermore, the shadow is registered by the photodetector as an electrical pulse of width We which is related to the fiber outer diameter do as:

$$d_o = W_e\frac{ds}{dt}$$

-
- Thus the fiber outer diameter may be quickly determined and recorded on the printer. The measurement speed is largely dictated by the inertia of the mirror rotation and its accuracy by the rise time of the shadow pulse.
- **Core diameter**
- The core diameter for step index fibers is defined by the step change in the refractive index profile at the core–cladding interface.
- Therefore the techniques employed for determining the refractive index profile (interferometric, near-field scanning, refracted ray, etc.) may be utilized to measure the core diameter.
- Graded index fibers present a more difficult problem as, in general, there is a continuous transition between the core and the cladding.
- In this case it is necessary to define the core as an area with a refractive index above a certain predetermined value if refractive index profile measurements are used to obtain the core diameter.
- Core diameter measurement is also possible from the near-field pattern of a suitably illuminated (all guided modes excited) fiber.
- The measurements may be taken using a microscope equipped with a micrometer eyepiece similar to that employed for off-line outer diameter measurements.
- However, the core–cladding interface for graded index fibers is again difficult to identify due to fading of the light distribution towards the cladding, rather than the sharp boundary which is exhibited in the step index case.

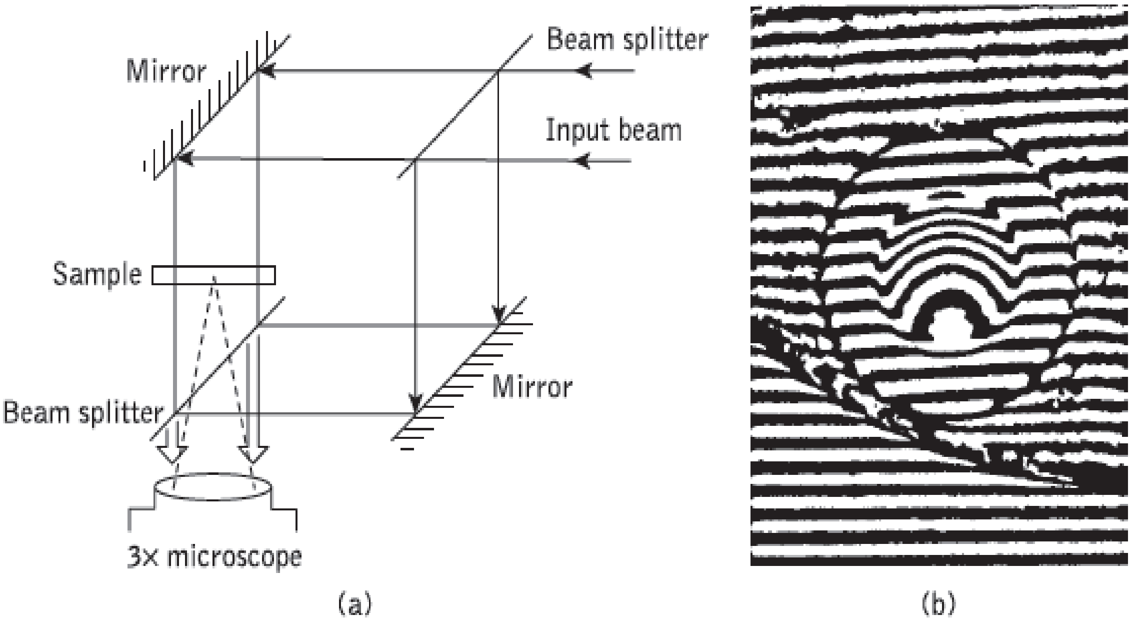
FIBER REFRACTIVE INDEX PROFILE MEASUREMENTS

- The refractive index profile determines fiber’s numerical aperture and the number of modes propagating within the fiber core.
- Hence a detailed knowledge of the refractive index profile enables the impulse response of the fiber to be predicted.
- Also, as the impulse response and consequently the information-carrying capacity of the fiber is strongly dependent on the refractive index profile, it is essential that the fiber manufacturer is able to produce particular profiles with great accuracy, especially in the case of graded index fibers (i.e. optimum profile).
- There is therefore a requirement for accurate measurement of the refractive index profile.
- These measurements may be performed using a number of different techniques each of which exhibit certain advantages and drawbacks.
- **Inter ferometric methods**
- **Near-field scanning method**

Refracted Near-Field method

Interferometric methods

- Interference microscopes (e.g. Mach–Zehnder, Michelson) have been widely used to determine the refractive index profiles of optical fibers.
- The technique usually involves the preparation of a thin slice of fiber (slab method) which has both ends accurately polished to obtain square (to the fiber axes) and optically flat surfaces.
- The slab is often immersed in an index-matching fluid, and the assembly is examined with an interference microscope.
- Two major methods are then employed, using either a transmitted light interferometer (Mach–Zehnder) or a reflected light interferometer (Michelson).
- In both cases light from the microscope travels normal to the prepared fiber slice faces (parallel to the fiber axis), and differences in refractive index result in different optical path lengths.
- When the phase of the incident light is compared with the phase of the emerging light, a field of parallel interference fringes is observed. A photograph of the fringe pattern may then be taken



- The fringe displacements for the points within the fiber core are then measured using as reference the parallel fringes outside the fiber core (in the fiber cladding).
- The refractive index difference between a point in the fiber core (e.g. the core axis) and the cladding can be obtained from corresponds to a number of fringe displacements. This difference in refractive index δn is given by

$$\delta n = \frac{q\lambda}{x}$$

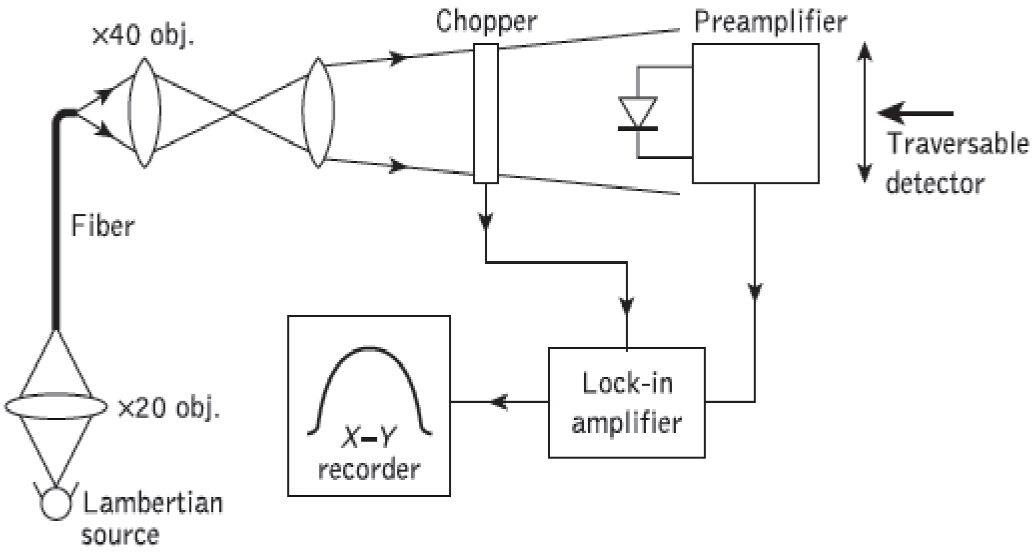
- where x is the thickness of the fiber slab and λ is the incident optical wavelength.
- The slab method gives an accurate measurement of the refractive index profile.
- A limitation of this method is the time required to prepare the fiber slab.

Near-field scanning method

- The near-field scanning or transmitted near-field method utilizes the close resemblance that exists between the near-field intensity distribution and the refractive index profile, for a fiber with all the guided modes equally illuminated.
- It provides a reasonably straightforward and rapid method for acquiring the refractive index profile.
- When a diffuse Lambertian source (e.g. tungsten filament lamp or LED) is used to excite all the guided modes then the near-field optical power density at a radius r from the core axis $P\text{D}(r)$ may be expressed as a fraction of the core axis near-field optical power density $P\text{D}(0)$ following

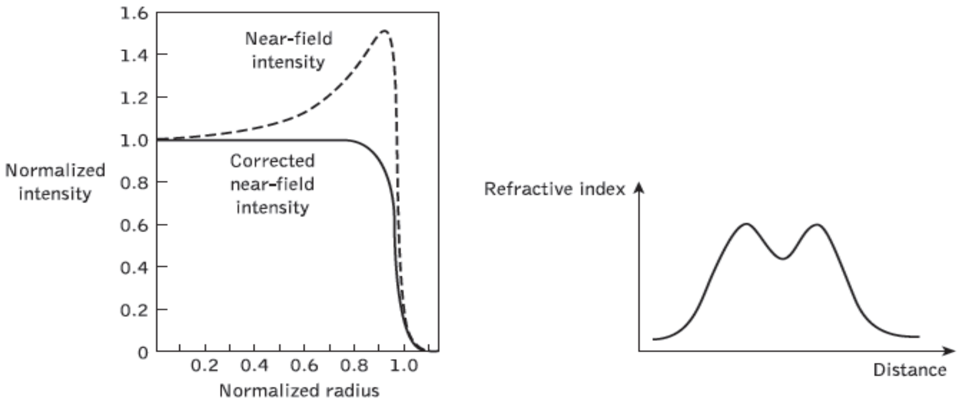
$$\frac{P_D(r)}{P_D(0)} = C(r, z)\left[\frac{n_1^2(r) - n_2^2}{n_1^2(0) - n_2^2}\right]$$

where $n_1(0)$ and $n_1(r)$ are the refractive indices at the core axis and at a distance r from the core axis



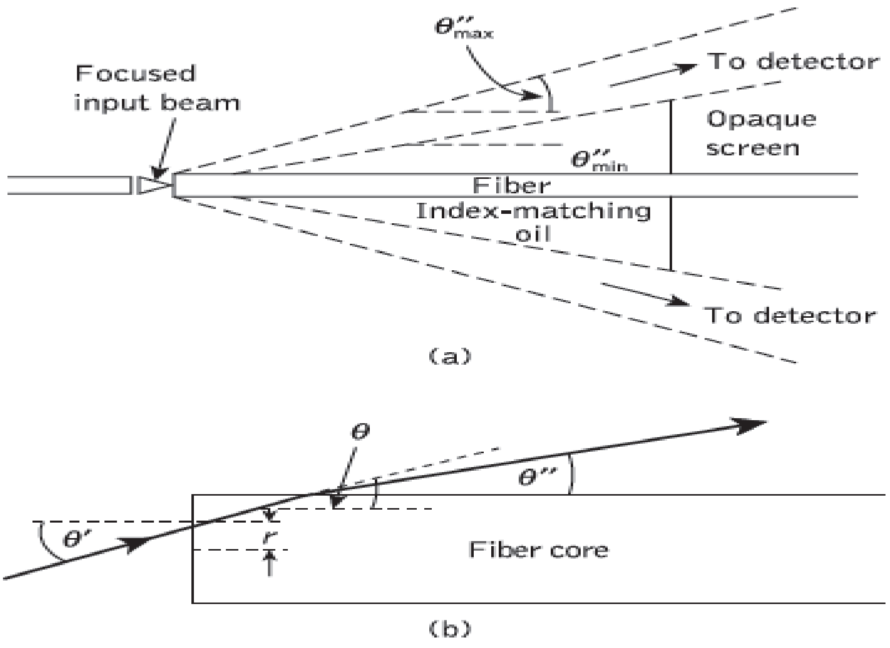
- n_2 is the cladding refractive index and $C(r, z)$ is a correction factor.
- The correction factor which is incorporated to compensate for any leaky modes present in the short test fiber may be determined analytically.
- A set of normalized correction curves is given.
- The transmitted near-field approach is, not similarly recommended for single-mode fiber.
- An experimental configuration is shown in above figure.
- The output from a Lambertian source is focused onto the end of the fiber using a microscope objective lens.
- A magnified image of the fiber output end is displayed in the plane of a small active area photodetector (e.g. silicon *p–i–n* photodiode).
- The photodetector which scans the field transversely receives amplification from the phase-sensitive combination of the optical chopper and lock-in amplifier.
- Hence the profile may be plotted directly on an *X–Y* recorder.
- However, the profile must be corrected with regard to $C(r, z)$ which is very time consuming.
- Both the scanning and data acquisition can be automated with the inclusion of a minicomputer.

- The test fiber is generally 2 m in length to eliminate any differential mode attenuation and mode coupling.
- A typical refractive index profile for a practical step index fiber measured by the near-field scanning method is shown in figure.
- It may be observed that the profile dips in the center at the fiber core axis.
- This dip was originally thought to result from the collapse of the fiber preform before the fiber is drawn in the manufacturing process but has been shown to be due to the layer structure inherent at the deposition stage.



(a) (b)

Refracted Near-Field



- The Refracted Near-Field (RNF) or refracted ray method is complementary to the transmitted near-field technique.
- But has the advantage that it does not require a leaky mode correction factor or equal mode excitation.

- Moreover, it provides the relative refractive index differences directly without recourse to external calibration or reference samples.
- The RNF method is the most commonly used technique for the determination of the fiber refractive index profile and it is the reference test method for both multimode and single-mode fibers.
- A schematic of an experimental setup for the RNF method is shown in figure.
- A short length of fiber is immersed in a cell containing a fluid of slightly higher refractive index.
- A small spot of light typically emitted from a 633 nm He–Ne laser for best resolution is scanned across the cross-sectional diameter of the fiber.
- The measurement technique utilizes that light which is not guided by the fiber but escapes from the core into the cladding.
- Light escaping from the fiber core partly results from the power leakage from the leaky modes which is an unknown quantity.
- The effect of this radiated power reaching the detector is undesirable and therefore it is blocked using an opaque circular screen, as shown in Figure a.
- The refracted ray trajectories are illustrated in figure (b) where θ' is the angle of incidence in the fiber core, θ is the angle of refraction in the fiber core and θ'' constitutes the angle of the refracted inbound rays external to the fiber core.
- Any light leaving the fiber core below a minimum angle θ''_{min} is prevented from reaching the detector by the opaque screen figure (a).
- Moreover, it may be observed from figure (b) that this minimum angle corresponds to a minimum angle
- However, all light at an angle of incidence $\theta' > \theta'_{min}$ must be allowed to reach the detector.
- To ensure this process it is advisable that input apertures are used to limit the convergence angle of the input beam to a suitable maximum angle θ'_{max} corresponding to a refracted angle θ''_{max}.
- In addition, the immersion of the fiber in an index matching fluid prevents reflection at the outer cladding boundary.
- Hence all the refracted light emitted from the fiber at angles over the range θ''_{min} to θ''_{max} may be detected.
- The detected optical power as a function of the radial position of the input beam $P(r)$ is measured and a value $P(a)$ corresponding to the input beam being focused into the cladding is also obtained.
- The refractive index profile $n(r)$ for the fiber core is then given
- $n(r) = k_1 - k_2 P(r)$

- $n(r) = n_2 + n_2\cos\theta''_{min}(\cos\theta''_{min} - \cos\theta'_{max})\{P(a)-P(r)\}/P(a)$
- It is clear that $n(r)$ is proportional to $P(r)$ and hence the measurement system can be calibrated to obtain the constants k_1 and k_2.

PREAMPLIFIERS

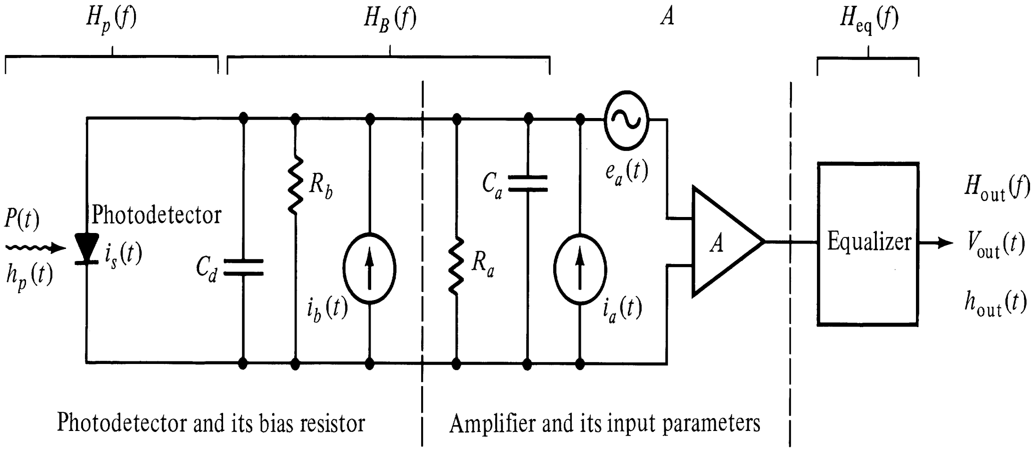
- The receiver amplifiers are the front-end amplifier.
- **Types of preamplifiers:**
- 1.Low impedance preamplifiers.
- 2.High impedance preamplifiers.
- 3.Trans impedance preamplifiers
- A preamplifier should satisfy the following requirements:
- Low Noise level
- High Bandwidth
- High Dynamic range
- High Sensitivity
- High Gain

LOW IMPEDANCE PREAMPLIFIER

- A photodiode operates into a low impedance amplifier.
- Bias or load resistor R_b is used to match the amplifier impedance.
- The value of R_b in conjunction with the amplifier input capacitance is such that the preamplifier, bandwidth is equal or greater than that the signal bandwidth.
- This limits their use to special short distance applications.

HIGH IMPEDANCE PREAMPLIFIER

- The goal is to reduce all sources of noise to the absolute minimum
- This is accomplished by decreasing the input capacitance through the selection of low capacitance high frequency devices by selecting a detector with low dark currents and by minimizing the thermal noise contributed by the biasing resistors.
- The thermal noise can be reduced by using a high impedance amplifier with large photodetector resistor hence called high impedance preamplifier.

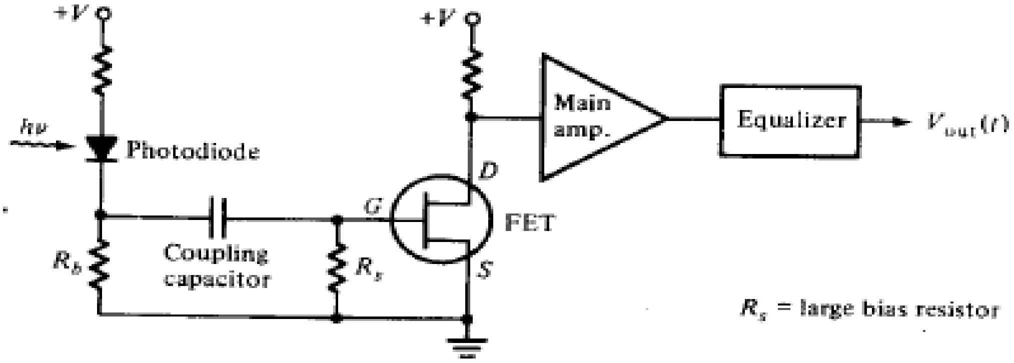


HIGH IMPEDANCE FET AMPLIFIERS

- The principal noise sources are thermal noise associated with FET channel conductance thermal noise from the load or feedback resistor and shot noise arising from gate leakage current and fourth noise source is FET 1/f noise.
- The input current noise spectral density S_1 is

$$S_{I,\,\mathrm{FET}} = \frac{4k_BT}{R_a} + 2qI_{\mathrm{gate}}$$
$$\simeq 2qI_{\mathrm{gate}}$$

$$S_E = \frac{4k_BT\Gamma}{g_m}$$

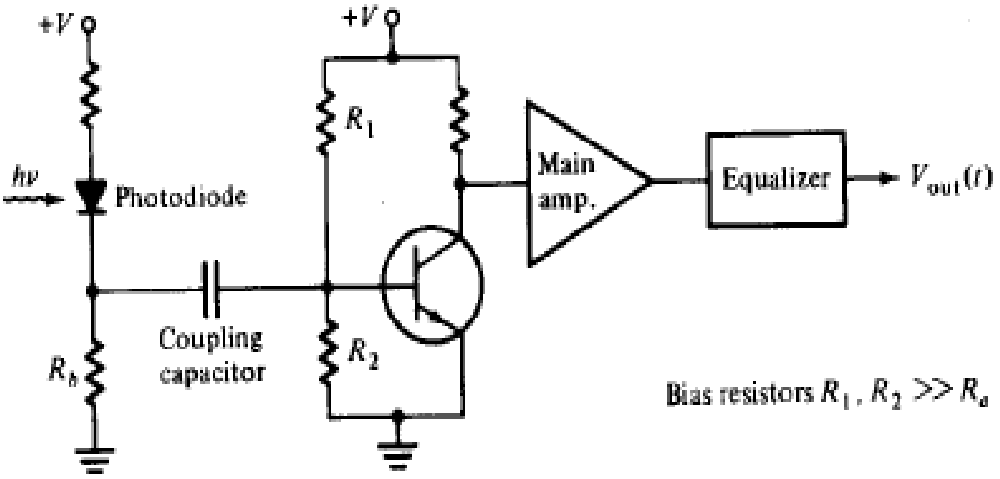


- The thermal noise two characteristics W at the equalizer output is then,

- The 1/f noise corner frequency f_c is defined as the frequency at which 1/f noise, which dominates the FET noise at low frequency has a 1/f power spectrum becomes equal to the high frequency channel noise.

$$W = \frac{1}{q^2 B}\left(2qI_{\text{gate}} + \frac{4k_B T}{R_b} + \frac{4k_B T\Gamma}{g_m R_b^2}\right) I_2 + \left(\frac{2\pi C}{q}\right)^2 \frac{4k_B T\Gamma}{g_m} I_3 B$$

HIGH IMPEDANCE BIPOLAR TRANSISTOR AMPLIFIERS



$$R_{\text{in}} = \frac{k_B T}{qI_{BB}}$$

$$S_I = 2qI_{BB} = \frac{2k_B T}{R_{\text{in}}}$$

$$W = \frac{T_b}{q^2} 2k_B T\left[\left(\frac{1}{R_{\text{in}}} + \frac{2}{R_b} + \frac{R_{\text{in}}}{\beta R^2}\right) I_2 + \frac{(2\pi C)^2}{T_b^2}\frac{R_{\text{in}}}{\beta} I_3\right]$$

$$S_E = \frac{2k_B T}{g_m}$$

$$g_m = \frac{qI_c}{k_B T} = \frac{\beta}{R_{\text{in}}}$$

- **LIMITATIONS:**
- 1.For broadband application equalization is required.
- 2.It has limited dynamic range.

TRANS IMPEDANCE AMPLIFIER

- This is basically a higher gain high impedance amplifier with feedback provided to the amplifier through R_f .This designer yields both low noise and large dynamic range.

$$R_b' = \frac{R_b R_f}{R_b + R_f}$$

$$W_{TZ} = \frac{T_b}{q^2}\left(S_I + \frac{4k_B T}{R_b'} + \frac{S_E}{(R')^2}\right)I_2 + \frac{(2\pi C)^2}{q^2 T_b} S_E I_3$$

$$\frac{1}{R'} = \frac{1}{R} + \frac{1}{R_f} = \frac{1}{R_a} + \frac{1}{R_b} + \frac{1}{R_f}$$

$$W_{TZ} = W_{HZ} + \frac{T_b}{q^2}\frac{4k_B T}{R_f} I_2$$

$$H(f) = \frac{AR}{1 + j2\pi RCf}$$

$$B_{TZ} = \frac{A}{4RC}$$

UNIT V OPTICAL NETWORKS AND SYSTEM TRANSMISSION

Basic Networks

SONET / SDH

Broadcast and select WDM Networks

Wavelength Routed Networks

Non linear effects on Network performance

Link Power budget

Rise time budget

Noise Effects on System Performance

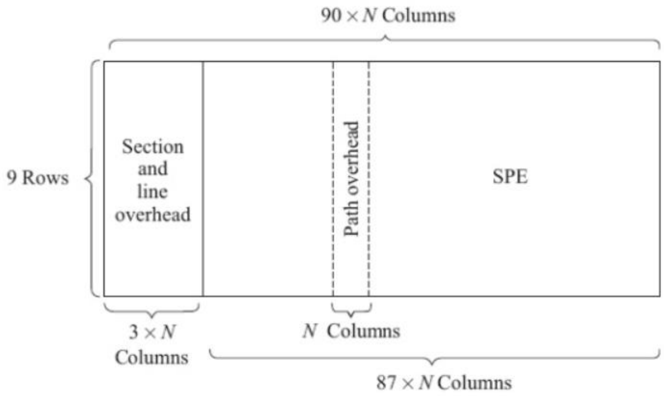
Operational Principles of WDM Performance of WDM + EDFA system

Solutions – Optical CDMA – Solitons in Optical Fiber

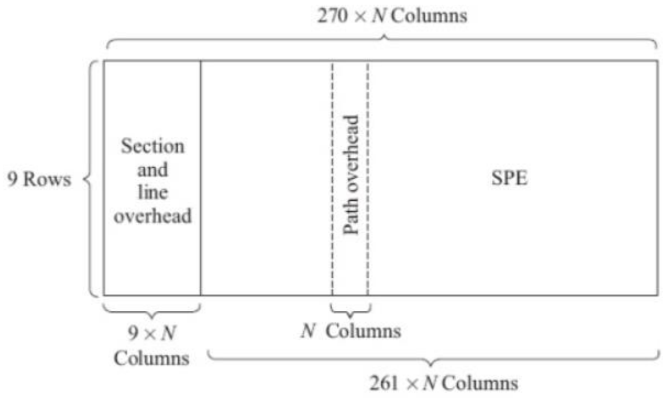
Ultra-High-Capacity Networks.

SONET/SDH

- 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 phycal 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 810*n* 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.



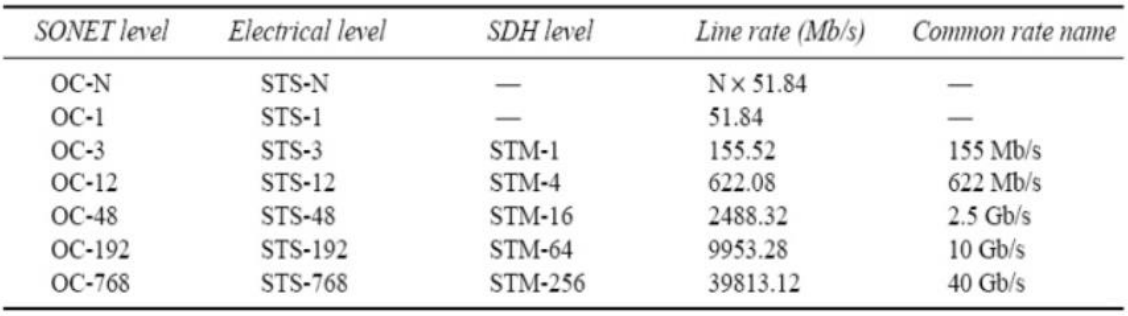
(*a*)



(*b*)

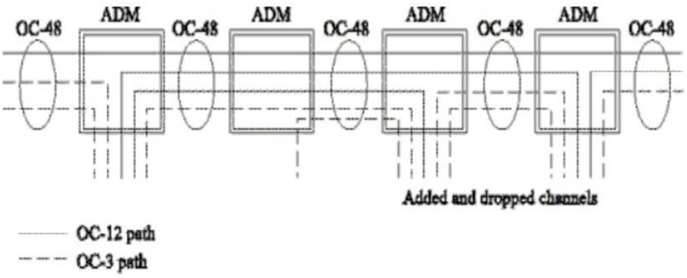
Common values of OC-N and STM-N:

- 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 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 Add Drop Multiplexers:

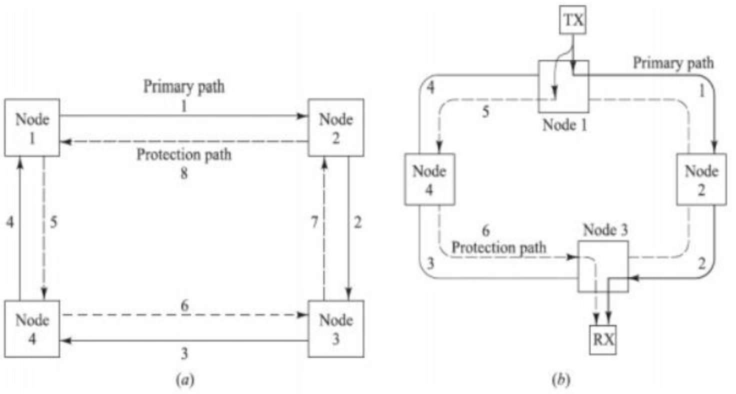


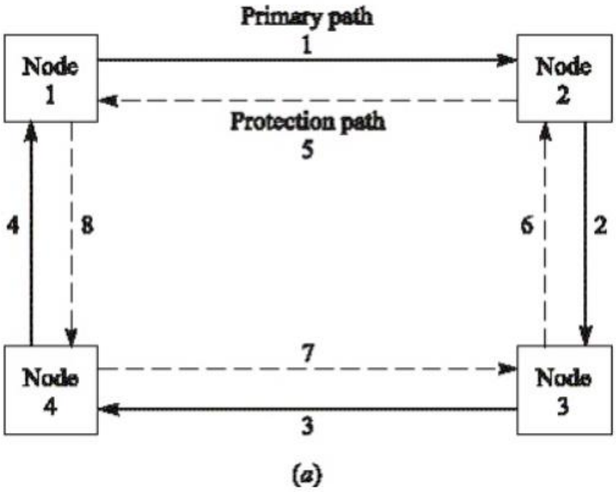
SONET ADM is a fully synchronous, byte oriented device, that can be used add/drop OC sub-channels within an OC-*N* signal

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

SONET/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)



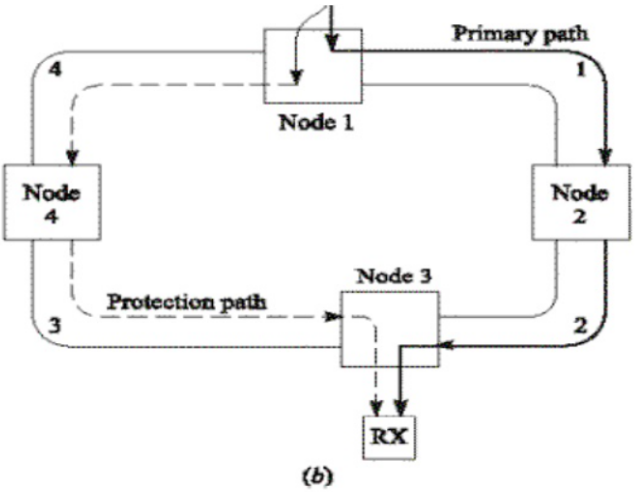


Ex: Total capacity OC-12 may be divided to four OC-3 streams, the OC-3 is called a path here

2-Fiber UPSR Protection:

Rx compares the signals received via the primary and protection paths and picks the best one

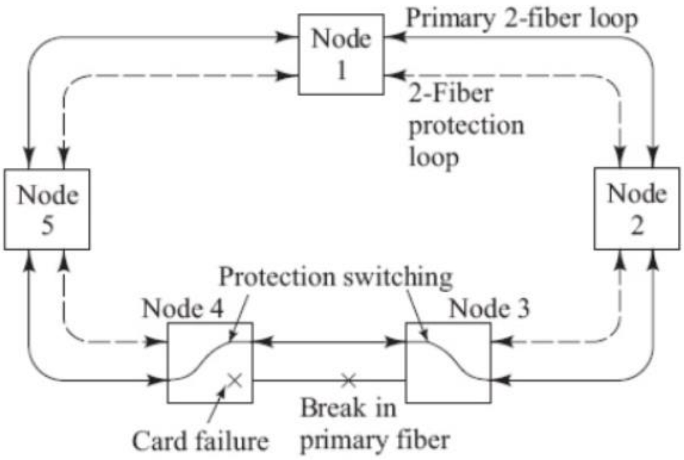
Constant protection and automatic switching



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

All-optical WDM networks have full potential of optical transmission capacity and versatility of communication networks beyond SONET architectures.

- These networks can be classified as

(1) Broadcast-and-select techniques

(2) Wavelength-routing networks.

- Broadcast-and select techniques employing passive optical stars, buses and wavelength routers are used for local networks can be classified as

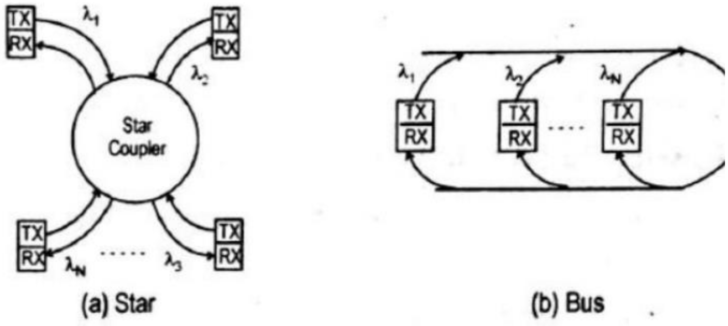
(1) Single-hop networks

(2) Multi-hop networks

- Single hop refers to network where information transmitted in the form of light reaches its destination without being converted to an electrical form at any intermediate point. In a multi hop network, intermediate electro-optical conversion can occurred.

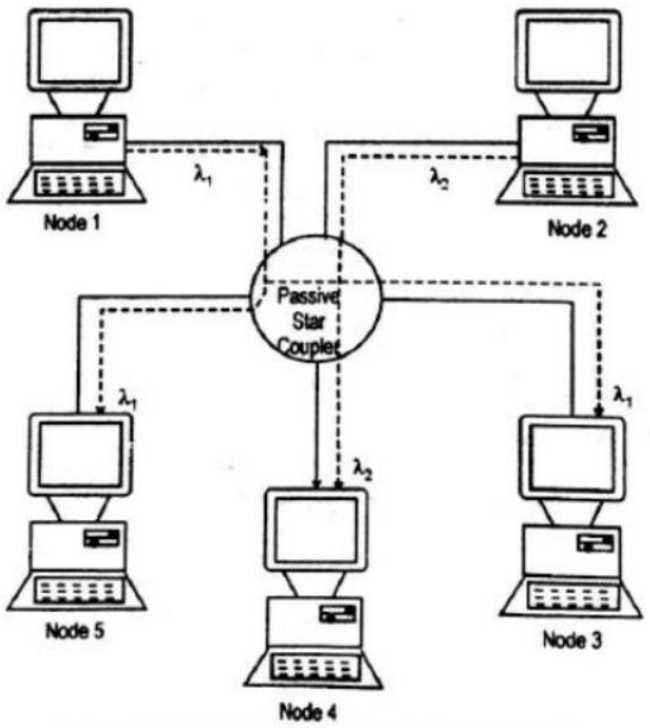
Broadcast and Select Signal Hop Network

- Two alternate physical architectures for a WDM-based local network have n sets of transmitters and receivers are attached to either a star coupler or a passive bus.



Each transmitter sends its information at a fixed wavelength.

- All the transmissions from the various nodes are combined in a pasive star. Coupler or coupled onto a bus and sent out to all receivers.
- An interesting point to note is that the WDM setup is protocol transparent.

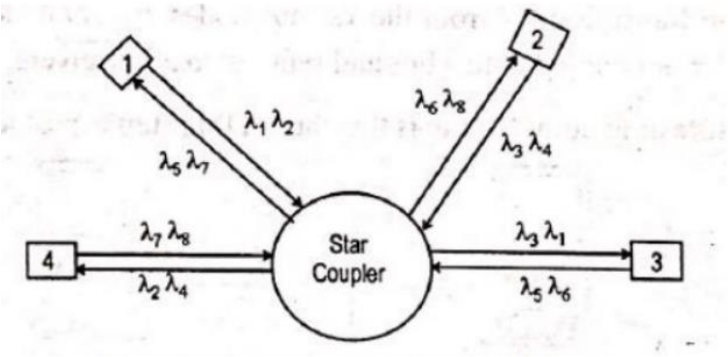


Protocol transparent means that different sets of communicating nodes can use different information exchange rules (protocols) without affecting the other nodes in the network.

- The architectures of single-hop broadcast-and-select networks are fairly simple, there needs to be careful dynamic coordination between the nodes.
- A transmitter sends its selective filter to that wavelength.
- Two sending stations need to coordinate their transmission so tha collisions of information streams at the some wavelength do not occur.

Broadcast and Select Multihop Network

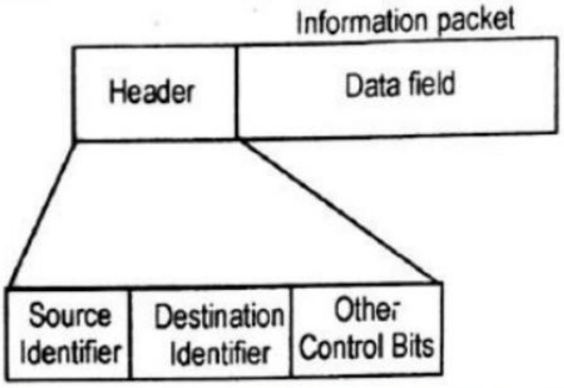
- Drawback of single-hop networks is the need for rapidlyt unable lasers or receiver optical fibers.
- This drawback can be overcome by the designs of multihop networks.
- Multihop networks do not have direct paths between each node pair.
- Each node has a small number of fixed tuned optical transmitter and receivers.



An example, a four node broadcast and select multihop network where each node transmits on one set of two fixed wavelengths and receives on another set of two fixed wavelengths.

· Information destined for other nodes will have to be routed through intermediate stations.

· Considering the operation, a simplified transmission shceme in which message are sent as packets with a data field and an address header containing source and destination identifiers (i.e,. routing information) with control bits.



At intermediate node, the optical signal is converted to an electrical format.

· The address header is decoded to examine the routing information field, which will indicate where the packet should go.

· Routing information is used to send the electronic packets from optical transmitter to the next node in the logical path toward its final destination.

· **Advantage:** There are no destination conflicts or packet collisions in the network.

· For H hops between nodes, there is a network throughput penalty of at least 1/H.

The Shuffle Net Multihop Network

· Various topologies for multihop lighwave networks are

(1) The shuffle net graph

(2) The de Bruijin graph

(3) He toroidal Manhattan street network

- A scheme called the perfect shuffle is widely used to form processor interconnect patterns in multiprocessors.

- For optical networks, the logical configuration consists of a cylindrical arrangement of k column, each having p nodes. Where P is the number of fixed transceiver pairs per node.

- The total number of nodes is then

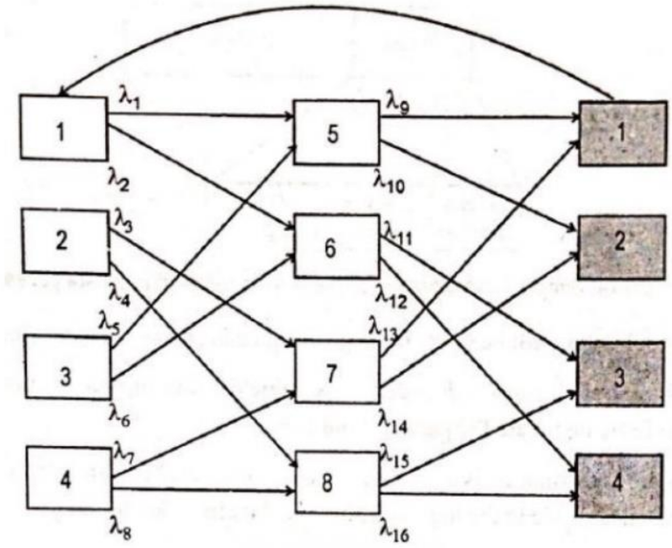
$$N = kp^k$$

where $k = 1, 2, 3, \ldots$

$p = 1, 2, 3, \ldots$

- **The total number of wavelengths N_λ needed in the network is**

$$N_\lambda = {}_pN = kp^{k+1}$$



- a (p,k)=(2,2) shuffle net, where the (k+1)th column represents the completion of a trip around the cylinder back to the first column.

- Performance parameter for the shuffle net is the average number of hops between any randomly chosen nodes.

- Since, all nodes have p output wavelength, p nodes can be reached from any node in one hop, p2 additional nodes can be reached in two hope, until all the (pk-1) other nodes are visited.

- The maximum number of hops is

$$H_{max} = 2k - 1$$

- Consider figure above, the connections between nodes 1 and 5 and nodes 1 and 7. In first case, the hop number is one.

- In second case three hops are needed with routes 1- 6 – 7 or 1 – 5 – 2 -7.?

- The average of hops Bar H of a shuffle net is

- The average number of hops $\overline{H}$ of a Shuffle Net is

$$\overline{H} = \frac{1}{N-1}\left[\sum_{j=1}^{k-1} j\,p^{j} + \sum_{j=0}^{k-1}(k+j)+(p^{k}-p^{j})\right]$$

$$= \frac{kp^{k}(p-1)(3k-1)-2k(p^{k}-1)}{2(p-1)(kp^{k}-1)}$$

- In multiphopping, part of the capacity of a particular link directly connecting two nodes is actually utilized for carrying between them.
- The rest of thelink capacity is used to forward messages from other nodes.
- The system has Np=kpK+1 links, the total network capacity C is

$$C = \frac{kp^{k+1}}{\overline{H}}$$

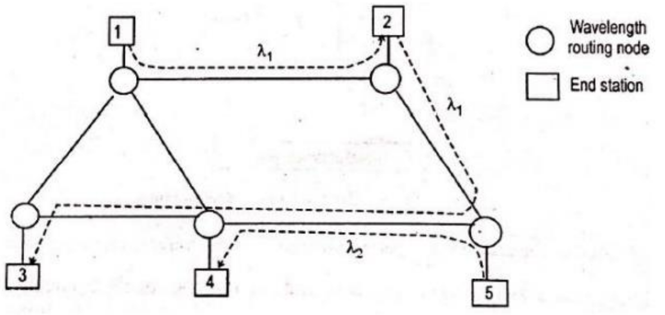
- The per-user throughput δ is

$$\delta = \frac{C}{N} = \frac{P}{\overline{H}}$$

- Different (p,k) combination result in different throughputs, to get a better network performance.

Wavelength Routed Networks

- Two problems arise in broadcast and select networks,
- More wavelengths are needs as the number of nodes in the network grows.
- Without the widespread are use of optical booster amplifier, due to this splitting losses is high.
- Wavelength routed networks overcome these limitations through wavelength reuse, wavelength conversion, and optical switching.
- The physical topology of a wavelength routed network consists of optical wavelength routers interconnected by pair of point-to-point fiber link in an arbitrary mesh configuration.



- Each link can carry a certain number off wavelength which can be directed independently to differently output paths at a node.
- Each node may have logical connections with several other nodes in the network, where each connection uses a particular wavelength.
- The paths taken by any two connections do not overlap, they can use the same wavelength.

1. Optical Cross Connect

The concept of an optical cross connect architecture is the physical path structure, have a high degree of path modularity, capacity scaling, and flexibility in adding or dropping channels at a user site can be achieved.

- The physical path structure is called as path layer.
- These cross connects (OXCs) operate in the optical domain and can route very high capacity WDM data streams over a network of interconnected optical paths.

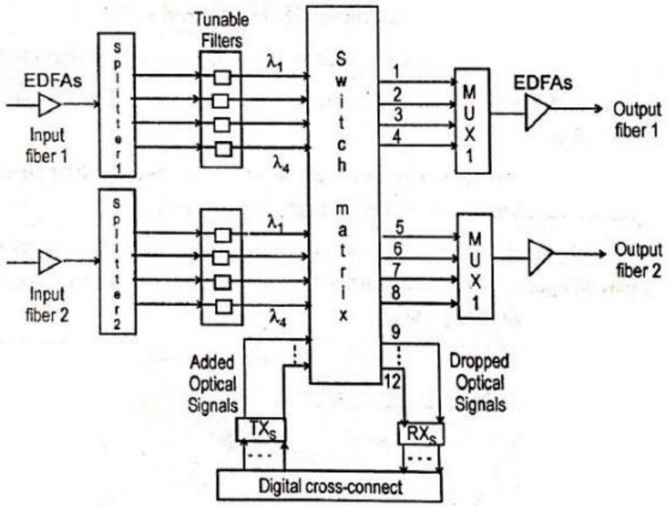


Figure 5.11 Optical Cross Connect Architecture

OXC architecture uses space switching without wavelength conversion. The space switching can be constructed of a cascade of electronically controlled opticaldirectional-coupler elements or semiconductor-optical-ampliier switching gates. Each of the input fiber carries a M wavelengths. The input, arriving aggregate if signal wavelength is amplified and divided into N streams by a power splitter. Tunable filter then select individual wavelengths, which are directed to an optical space switching matrix.

A waveguide grating demultiplexer could be used to divide the incoming aggregate stream into individual wavelength channels. The switch matrix directs the channels either output lines, or to a particular receiver attached to the OXC at outputs ports 9 through 12. Signals that are generated locally by a user get connected electrically via the digital cross connect matrix (DXC) to an optical transmitter.

They enter the switch matrix, which directs them to the appropriate output line. The M output lines, each carrying separate wavelength, are fed into a wavelength multiplexer ('mux' and a demultiplexer is 'demux') to form a single aggregate output stream. An optical amplifier to boost the signal level for transmission over the trunk fiber.

2. Performance Evaluation of Wavelemgth Conversion

These effects are

(1) Probability models
(2) Deterministic algorithms

- The benefits are greater in a mesh network than in a ring or fully connected network.

The Effect of Wavelength Conversion

- Simple model, circuit switched networks is used.
- The probability that a wavelength is blocked along a path.
- It provides insight into the network performance improvement using wavelength conversion.
- Assume H links (or hops) between two nodes A and B.
- The expected number of busy wavelength on any link is ρF, where ρ is a measure of the fiber utilization along the path and F is the number of a available wavelengths per

Non Linear Effect on Network Performance

- Important Challenges In Designing Non Linear Networks Are:
- Transmission of the different wavelength channel at the highest possible bit rate.
- Transmission over the longest possible distance with the smallest number of optical amplifiers.
- Network architectures that allow simple and efficient operation, control and management.

The Various Signal Impairment Effect are as Follows

i. **Group Delay Dispersion (GVD)**, Which limits the bit rate by temporally spreading a transmitted optical pulse, dispersion induced pulse spreading can be minimized by WDM networks operation in a low dispersion window such as 1310 nm and 1550 nm.

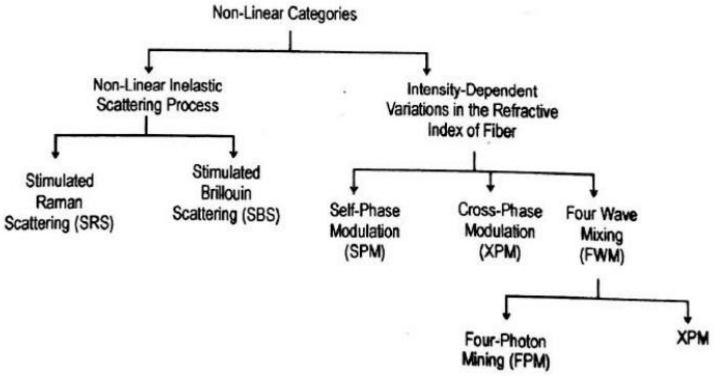
ii. Non-uniform gain across the desired wavelength range of EDFAs in WDM links.

iii. **Polarization Mode Dispersion (PMD)**, Which arises from orthogonal polarization modes traveling at a slightly different speeds owing to fiber birefringence.

iv. Reflections from splices and connectors that can cause instabilities in laser sources. These can eliminated by the use of optical isolators.

v. Non-linear inelastic scattering processes, which are interactions between optical signal and molecular or acoustic vibrations in a fiber.

v. Non-linear variations of the refractive index in a silica fiber that occur because the refractive index is dependent on intensity changes in the signal.

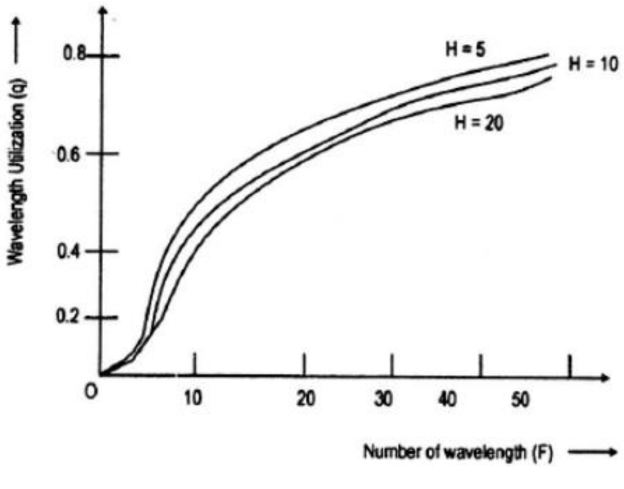


- A connection request between modes A and B is blocked if one of the H intervening fibers is full.
- The probability Pb’ that a the connection request from A to B is blocked is the probabity and fiber link with all wavelength F.

$$P_b' = 1 - (1 - \rho^F)^H$$

- If q is the achievable utilization for a given blocking probability in a network with wavelength conversion.

$$q=\left[1-(1-P_b')^{1/H}\right]^{1/F} \approx \left(\frac{P_b'}{H}\right)^{1/F}$$



The effect of path length is small, and q rapidly approaches I as F becomes large.

A Network Without Wavelength Conversion

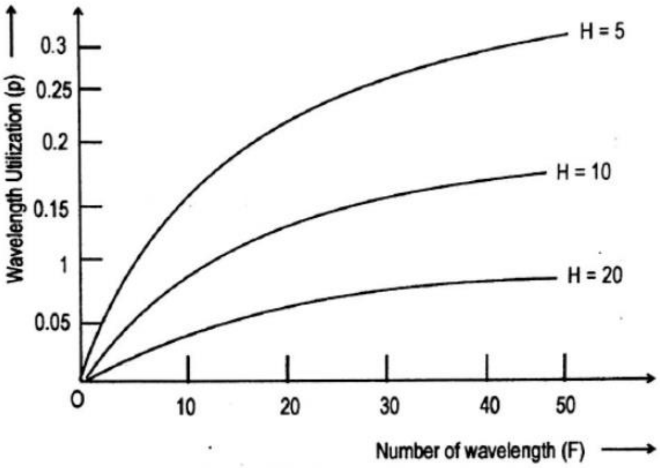
- A connection request between A and B can be honoured only if there is a free wavelength.
- The probability Pb that the connection request from A and B is blocked is the probability that each wavelength is used on at least one of the H links,

$$P_b = [1 - (1 - \rho)^H]^F$$

- Letting P be the achievable utilization for a given blocking probability in a network without wavelength conversions,

$$P = 1 - (1 - P_b^{1/F})^{1/H} \approx -\frac{1}{H} \ln (1 - P_b^{1/F})$$

- Where the approximation holds for large values of H and for Pb1/F not too close to unity.
- In this case, the achievable utilization is inversely proportional to the length of the path H between A and B.



- Here the effect of path length (i.e., the number of links) is dramatic.

To Measure the Benefit of Wavelength Conversion

- The gain G=q/P to be the increase in fiber or wavelength utilization for the same blocking probability.

- **From equation (5.25) and (5.27). Setting $P_b' = p_b$ we have**

$$G = q/P$$

$$G \equiv \frac{q}{p} = \frac{1-\left[(1-P_b)^{1/H}\right]^{1/F}}{1-\left(1-P_b^{1/F}\right)^{1/H}}$$

$$\approx H^{1-1/F}\,\frac{P_b^{1/F}}{-\ln\left(1-P_b^{1/F}\right)} \quad \cdots$$

- G as a function of H=5, 10 and 20 links for blocking probability for pb=10-3.
- F increases, the gain increases, peaks at about H/2
- The gain slowly decreases, since large trunking networks are more efficient.

1. Effective Length And Area

- The non-linear process can be depend on the transmission length, the cross-sectional area of the fiber, and the optical power level in the fiber.
- **Effective Length** Leff: Which takes into account power adsorption along the length of the fiber (i.e., optical power decays exponentially with length) is given by

$$L_{eff} = \frac{1}{p_0}\int_0^L p(z)\,dz = \int_0^L e^{-\alpha z}\,dz = \frac{1-e^{-\alpha L}}{\alpha}$$

- When there is a optical amplifier in a link, the effective length is the sum of the effective lengths of the individual spans between optical amplifiers.
- If the total amplified link length is LA and the span length between amplifier is L, the effective length is

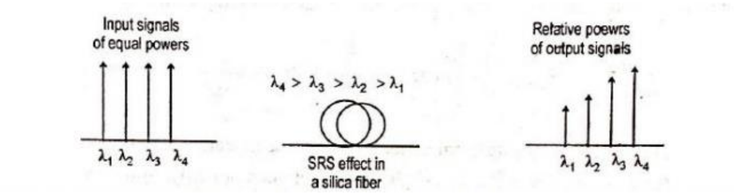
$$L_{eff} = \frac{1-e^{-\alpha L}}{\alpha}\,\frac{L_A}{L}$$

- The effects of non-linearities increase with the light intensity in a fiber. This light intensity is inversely propoetional to the cross-sectional area of the fiber.
- As a rule of thumb, standard non-dispersion-shifted single mode fibers have effective area Aeff=80µm2, dispersion-shifted fibers have effective area Aeff is 55µm2 and dispersion-compenstating fibers have effective areas is 20oµm2.

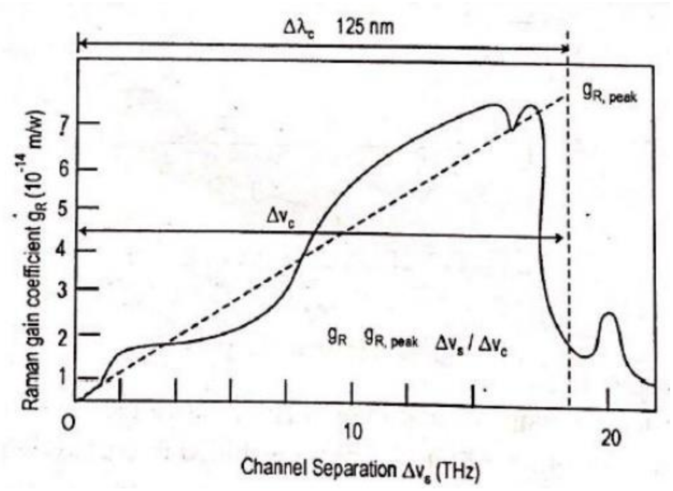
2. Stimulated Raman Scattering

- Stimulated Raman scattering is an interaction between light waves and the vibrational modes of silica molecules.

- If a photon with energy h*v*1 is incident on a molecule having a vibrational frequency vin, the molecule can absorb some energy from the photon.
- In interaction, the photon is scattered, thereby attaining a lower frequency v2 a corresponding lower energy h*v*2. The modified photon is called as stokes photon.
- The optical signal wave that is injected into a fiber is the source of the interacting photons, it is often called the pump wave, it supplies power from the generated wave.



- SRS can severely limit the performance of a multichannel optical communication system by transferring energy from short-wavelength channels to neighboring higher-wavelength channels. This is a broadband effect that can occur in both dirctions.
- The effects of SRS, consider WDM system has N channel equally spaced in a 30 nm band cantered at 1545 nm.
- Assume fout (j) is the fraction of power coupled from channel o to channel j



- The total fraction of power coupled out of 0 to all the other channel is

$$F_{out} = \sum_{j=1}^{N-1} F_{out}(j) = \sum_{j=1}^{N-1} g_{R,peak} \frac{j\Delta v_s}{\Delta v_c} \frac{PL_{eff}}{2A_{eff}}$$

$$= \frac{g_{R,peak}\,\Delta v_s\, PL_{eff}}{2\Delta v_c\, A_{eff}} \frac{N(N-1)}{2}$$

- The power penalty for this channel is -10 log(1-Fout)
- To keep power penalty <0.5 dB and Fout <0.1 use equation (5.31) with Aeff=55μm2, the criterion.

$$[NP]\,[N-1]\,\Delta\nu_s\, L_{eff} < 5 \times 10^{-3}\ \text{mW} .\ TH_z .\ km$$

where NP is the total power coupled into the fiber,

$(N-1)\Delta\nu_s$ is the total occupied optical bandwidth.

L_{eff} is the effective length.

3. Stimulated Brillouin Scattering

- Stimulated Brillouin scattering arises when light waves scatter from acoustic waves.
- Scattered wave propagates principally in the backward direction in single-mode fibers. This backward light experiences gain from the forward-propagating signals.
- The frequency of the scattered light experiences a Doppler shift given by

$$\nu_B = 2n\, V_S/\lambda$$

Where n is the index refraction, Vs is the velocity of sound in material.

- Interaction occurs Brillouin linewidth of Dvg=20MHz at 1550nm.
- For Vs=5760 m/s in fused silica, the frequency of the backward propagating light at 1550 nm is shifted by 11 GHz(0.99nm) rom the original signal.
- In a long fiber chain containing optical amplifiers, there are optical isolators to prevent backward scattered signals form entering the amplifier.
- SBS threshold power Pth is defined to be the signal power at which the backward light equal the fiber-input power.

$$P_{th} \approx 21\, \frac{A_{eff}\, b}{g_B L_{eff}} \left(1 + \frac{\Delta\nu_{source}}{\Delta\nu_B}\right)$$

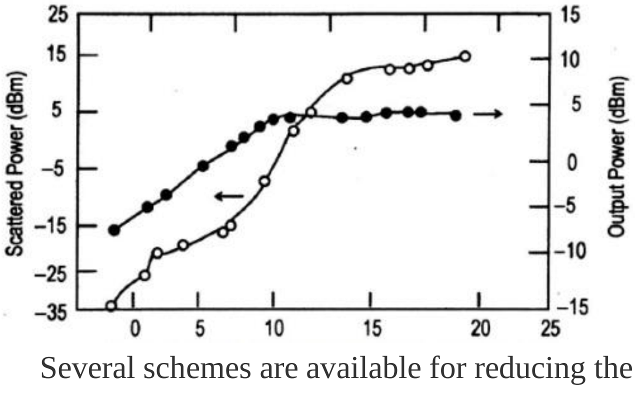
where A_{eff} is the effective cross-sectional area of propagating wave.

b is the polarization factor ($b = 1$ to 2).

L_{eff} is the effective length.

g_B is the Brillouing gain cocefficient (4×10^{-11} m/w).

- The SBS threshold power increase as the source linewidth becomes larger.



- Several schemes are available for reducing the power penalty effects of SBS as follows:

- Keeping the optical power per WDM channel below the SBS thresholds, for long-haul systems.

- Increasing the linewidth of the source, smince the gain bandwidth of SBS is very small. This can be achieved through direct modulation of the source.
- Slightly dithering the laser output in frequency, at roughly tens of kilohertz. The dither frequency should scale as the ratio of the injected power to the SBS threshold.

4. Cross Talk

Crosstalk: it is defined us the feed through of one channel signal into another channel.

Types Of Crosstalk:

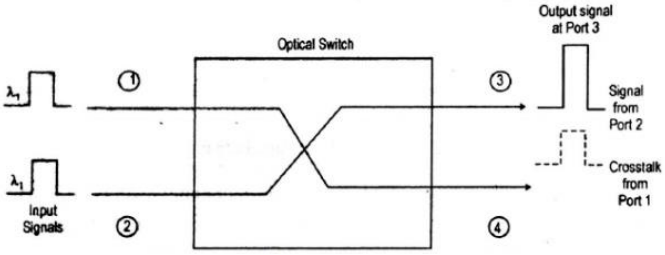
There are two types of crosstalk that can occur is WDM systems:

(1) Intrachannel crosstalk

(2) Interechannel crosstalk

(I)INTRACHANNEL CROSSTALK;

It arises when interfering signal is at the same wavelength as the desired signal. This effect is more severe than interchannel crosstalk, because the interference falls completely with in the receiver bandwidth.



Two independent signals, each at a wavelength l1, enter an optical switch.

This switch routes the signal entering port 1 to output port 4, and routes the signal entering port 2 to output port 3.

Within the switch, a spurious fraction of the optical power entering port 1 gets coupled to port 3, where it interferes with the signal from port 2.

(II) INTERCHANNEL CROSSTALK

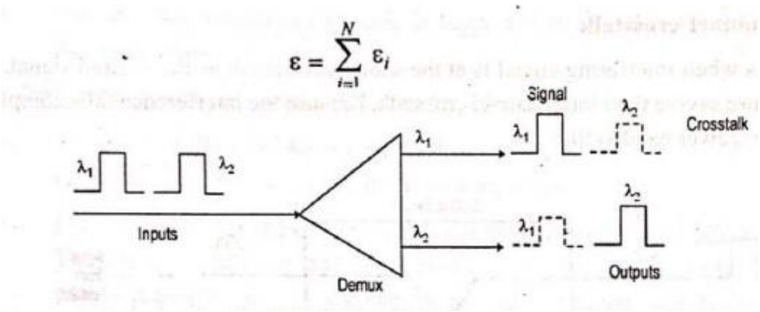
It arises when an interfering signal comes from a neighboring channel that operates at a different wavelength.

Power penalty of interchannel crosstalk is

$$\text{Penalty}_{inter} = -5 \log (1 - \varepsilon)$$

where ε is the a fraction of received crosstalk power.

Average crosstalk power eiP, the factor is from equation (5.43)



Example, a 1 –dB penalty arises when the intra channel level is 38.7 dB below the signal level and for inter channel crosstalk is 16 dB below the signal.

SOLITONS

Group velocity dispersion (GVD) causes most pulses to broaden in time as they propagate through an fiber.

A ‘solitons’ are pulses that travel along the fiber without change in shape or amplitude or velocity.

Soliton, takes advantage of non-linear effects in silica, particularly self phase modulation (SPM) resulting from the Kerr non-linearity, to overcome the pulse-broadening effects if GVD.

The term “soliton” refers to special kinds of waves that can propagate undistorted over long distances and remain unaffected after collision with each other.

In an optical communication system, solitons are very narrow, high intensity optical pulses that retain their shape through the interaction of balancing pulse dispersion with the non-linear properties of an optical fiber.

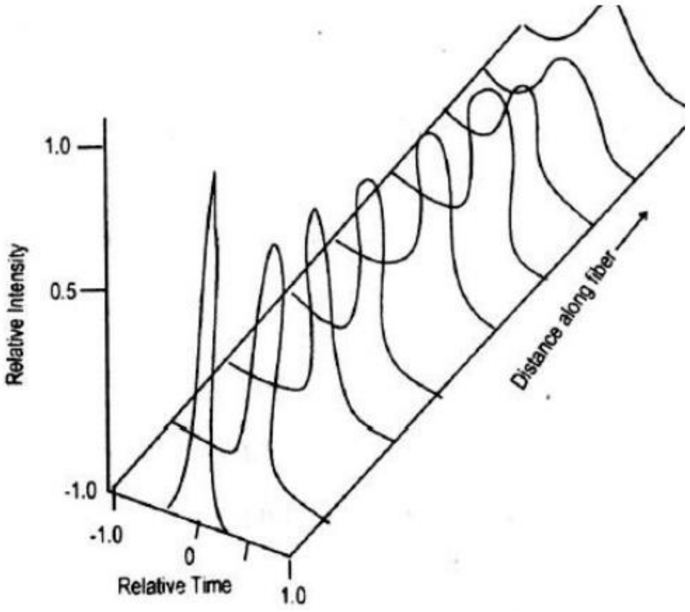
In an relative effects of SPM and GVD are controlled just right, and the appropriate pulse shape is chosen, the pulse compression routing from SPM can exactly offset the pulse broadening effect of GVD.

Fundamental Solitons- The family of pulse that do not change in shape are called fundamental solitons.

1. SOLITONS PULSE

When a pulse transverse a medium with a positive GVD parameter β2 for the constituent frequencies, the leading part of the pulse is shifted toward a longer wavelength (lower frequencies) so that the speed in that portion increases.

In the trailing half, the frequency arises. So the speed decreases. This causes the trailing edge to be further delayed.



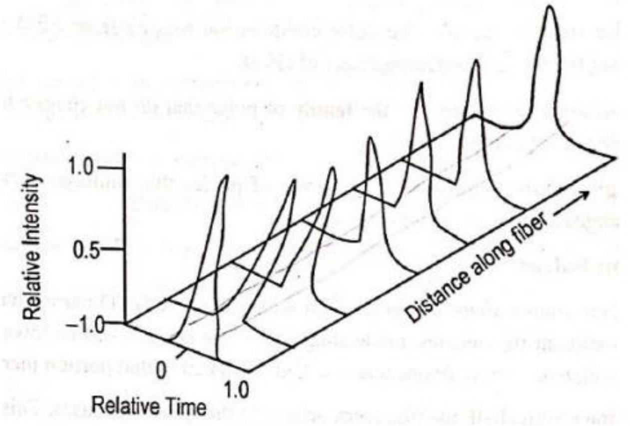
When a narrow high-intensity pulse traverse a medium with a negative GVD parameter for the constituting frequencies, GVD counteracts the chirp produced by SPM.

GND retards the low frequencies in the front end of the pulse and advances the high frequencies at the back.

The result is that the high-intensity sharply peaked soliton pulse changes neither its shape nor its spectrum as it travels along the fiber.

To derive the evolution of the pulse shape required for sodium transmission, one needs to consider the non-linear schrodinger (NLS) equation

$$-j\frac{\partial u}{\partial z}=\frac{1}{2}\frac{\partial^2 u}{\partial t^2}+N^2|u|^2u-j(\alpha/2)u \qquad \ldots (5.45)$$



Special soliton units to eliminate scaling constants.

The Three Right-Hand Terms in Equation (5.45)

(1) The first term represents GVD effects of the fiber.

(2) The second non-linear term denotes the fact that the refractive index of the fiber depends on the light intensity.

Through the self-modulation process, this physical phenomenon broadens the frequency spectrum of a pulse.

(3) The third term represents the effects of energy loss or gain.

2. SOLITONS PARAMETERS

Full-Width Half-Maximum (FWHM)

The full-width Half-maximum (FWHM) is a pulse is defined as the full width of the pulse at its half-maximum power level.

The FWHM Ts of the fundamental soliton pulse in normalized time is found from the relationship

$$\text{sech}^2(\tau) = \frac{1}{2}$$

where $\tau = \frac{\tau_s}{(2T_o)}$.

T_0 is the basic normalized time unit.

$$T_0 = \frac{T_S}{2\cosh^{-1}\sqrt{2}} = \frac{T_S}{1.7627} \approx 0.567\,T_S$$

Dispersion Length (Ldisp)

The normalized distance parameter (also called dispersion length) Ldisp is a characteristic length for the effects of the dispersion term.

Ldisp is a measure of the period of a soliton

$$L_{disp} = \frac{2\pi c}{\lambda^2}\frac{T_0^2}{D} = \frac{1}{[2\cosh^{-1}\sqrt{2}]^2}\frac{2\pi c}{\lambda^2}\frac{T_s^2}{D}$$

$$\approx 0.322\,\frac{2\pi c}{\lambda^2}\frac{T_s^2}{D}$$

where c is the speed of light,

λ is the wavlength in vacuum,

D is the dispersion of the fiber,

L_{disp} is measured in km.

The solition to equation for the fundamental solution is given by

$$u(z, t) = \mathrm{sech}\,(t) \exp\,(jz / 2)$$

Where sech (t) is the hyperbolic secant function. This is a bell-shaped pulse.

The phase term exp (jz/2) in equation has no influence on the shape of the pulse, the soliton is independent of z and hence is non-dispersive in the time domain.

For the NLS equation, to find the first-order effects of the dispersive and non-linear terms are just complementary phase shifts.

For a given by equation these phase shifts are

$$d\phi_{\text{non-line}} = |u(t)|^2\, dz = \mathrm{sech}^2(t)dz$$

For the non-linear process, and

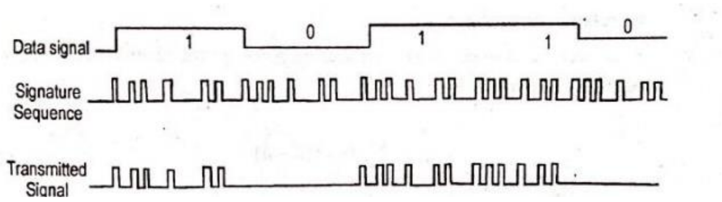
$$d\phi_{disp} = \left(\frac{1}{2u}\,\frac{\partial^2 u}{\partial t^2}\right)dz = \left[\frac{1}{2} - \sec h^2(t)\right]dz$$

Dispersion and non-linear phase shifts of a soliton pulse which sum is constant, which yields a common phase shift of z\2 for the entire pulse.

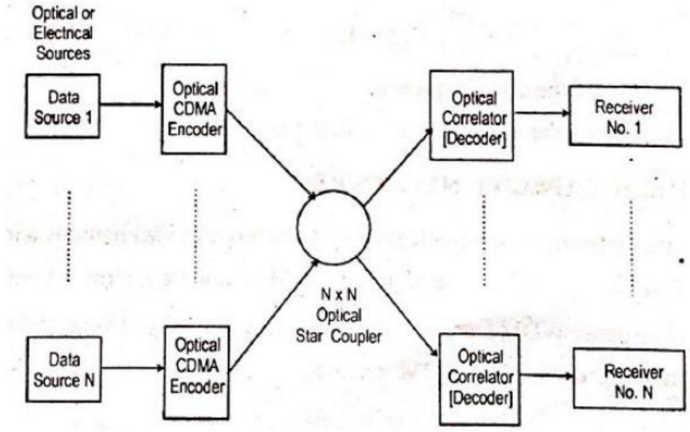
Since such a phase shift changes neither the temporal nor the spectral shape of a pulse, the soliton remains completely non-dispersive in both the temporal and frequency domain.

Optical CDMA

- The simplest configuration,CDMA achieves multiple access by assigning a unique code to each user.
- To communicate with another node, user imprint their agreed upon code onto the data. The receiver can then decode the bit stream by locking onto the code sequence.
- The principle of optical CDMA is based on spread-spectrum techniques.
- The concept is to spread the energy of the optical signal over a frequency band that is much wider than the minimum bandwidth required to send the information.
- Spreading is done by a code that is independent of the signal itself.
- On optical encoder is used to map each bit of information into the high-rate (longer-code-length) optical sequence.
- The symbols is the spreading code are called chips.
- The energy density of the transmitted waveform is distributed more or less uniformly over the entire spread-spectrum bandwidth.
- The set of optical sequences becomes a set of unique ‘address codes or signature sequences’ the individual network users.



- The signature sequence contains six chips. When the data signal contains 1 data bit, the six-chip sequence is transmitted, no chips are sent for a 0 data bit.
- Time-domain optical CDMA allows a number of users to access a network simultaneously, through the use of a common wavelength.
- Both asynchronous and synchronous optical CDMA techniques. In synchronous accessing schemes follow rigorous transmission schdules, the produce more successful transmission (higher throughputs) than asynchronous methods where network access is random and collisions between users can occurs.
- An optical CDMA network is based on the use of a coded sequence of pulses.
- The setup consists of N transmitter and receiver pairs interconnected in a star



To send information from node j to node k, the address code for node k is impressed upon the data by the encoder at node j.

At the destination, the receiver differentiates between codes by means of correlation detection.

Each receiver correlates its own address f(n) with the received signal s(n). The receiver output r(n) is

$$r(n) = \sum_{k=1}^{N} s(k)\, f(k-n)$$

If the received signal arrives at the correct destination, then s(n)=f(n).

- Equation represents an autocorrelation function, if s(n) not equal to f(n) the equation represents a cross-correlation function.

- For a receiver to be able to distinguish the proper address correctly, it is necessary to maximize the autocorrelation function and minimize the cross-correlation function.
- Prime-sequence codes and optical orthogonal codes (OOCs) are the commonly used spreading sequences in optical CDMA systems.
- An OOC systems the number of simultaneous user an is bounded by

$$N \le \left\lfloor \frac{F-1}{K(K-1)} \right\rfloor$$

ULTRA HIGH CAPACITY NETWORKS

- Advance of optical communication systems has provide channels with enormous bandwidth at least 25THz and dense WDM technology, ultrafast optical TDM.
- To using dense WDM techniques to increase the capacity of long-haul transmission link and ultrafast optical TDM schemes.

These are particularly attractive in LAN or MANs

TDM Schemes To Shared-Media Local Neteorks Have Two Methods:

(1) Bit-interleaved TDM.

(2) Time-slotted TDM.

1. Ultra High Capacity WDM Networks

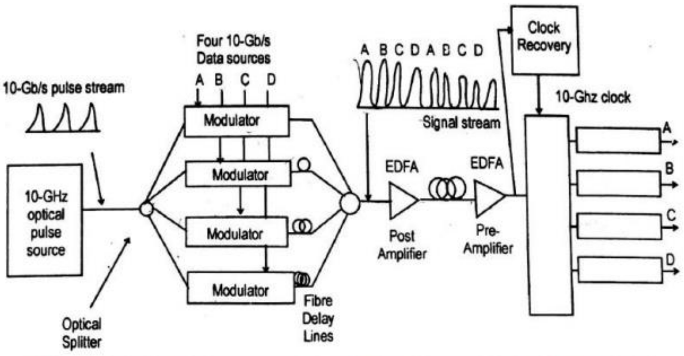
- Two popular approaches are used to achieve increased capacity.
    - to widen the spectral bandwidth of EDFAs from 30 to 80 nm, by using broadening techniques.
- Increasing the capacity of a WDM link is to improve the spectral efficiency of the WDM signals.
- Most of the demonstrations use a rate of 20 Gb/s for each individual wavelength to avoid non-linear effects.

Examples are,

(1) A 50-channel WDM system operating at an aggregated 1-Tb/s rate over a 600 km link.

(2) A 132-channel WDM system operating at an aggregated 2.6 Tb/s rate over a 120-km/link.

2. Bit-Interleaved Optical TDM



- Repetition rate typically ranges from 2.5 to 10 Gb/S, which corresponds to the bit rate of the electric data tributaries feeding the system.
- An optical splitter divides the pulse train into N separate streams.
- The pulse streams is 10 Gb/S and N=4, each of these channels is then individually modulated by an electrical tributary data source at a bit rate B.
- The modulated outputs are delayed individually by different fractions of the clock period, and are then interleaved through an optical combiner to produce an aggregate bitrate of NXB.
- Optical post amplifier and preamplifier are generally included in the link to compenstate for splitting and attenuation loss.
- At the receiving end, the aggregate pulse stream is demultiplexed into the original N independent data channels for further signal processing.
- A clock-recovery mechanism operating at the base bit rate B is required at the receiver to drive and synchronize the demultiplexer.

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