FIBER OPTIC COMMUNICATIONS

EC324/1 (R20): FIBER OPTIC COMMUNICATION

UNIT – I

INTRODUCTION: Historical development, Elements of an Optical Fiber transmission link, Advantages of Optical Fibers, Applications of Optical Fiber, Ray Theory Transmission, Total internal reflection, Acceptance angle, Critical angle, Numerical Aperture. Fiber types: Step Index, Graded Index: Modes of Propagation: single mode and multimode fibers, Fiber materials.

UNIT – II

TRANSMISSION CHARACTERISTICS OF OPTICAL FIBERS: Attenuation, absorption, scattering and bending losses in fibers, Dispersion: Inter model and intra model. FIBER OPTIC COMPONENTS: Splicing, Connectors, Connection losses, Fiber Optic couplers, Fiber Optic Switches.

UNIT – III

OPTICAL SOURCES: General characteristics, Principles of Light Emission. Light Emitting Diodes Types-Planar, Dome, Surface emitting, Edge emitting, Super luminescent LED's. LED Characteristics – Optical output power & efficiency, output spectrum, modulation bandwidth, reliability. LASER: Working of DH injection laser, DFB laser and Threshold condition for lasing. DETECTORS: Principles of photo detection. PIN Photodiode, Avalanche Photodiode and their characteristics.

UNIT – IV OPTICAL FIBER SYSTEMS: Optical Transmitter Circuits - source limitations, LED drive circuits. Optical Receiver Operation-Digital system transmission, error sources, receiver configuration, Preamplifier types, Digital receiver performance-probability of error, Quantum limit, System considerations – Link power budget, rise time budget, Advanced Multiplexing Strategies – OTDM, WDM.

UNIT – V

OPTICAL FIBER MEASUREMENTS: Numerical Aperture, attenuation, refractive index, dispersion losses, cutback and OTDR. OPTICAL NETWORKS: Basic Networks. Network Topologies, Performance of passive linear buses. SONET/ SDH: Transmission formats and speeds, Optical interfaces, SONET/SDH Rings, SONET/ SDH Networks

TEXT BOOKS:

1) John M Senior, Optical Fiber Communications: Principles and Practice, 2nd Edition, PHI, 2002.

2) Henry Zanger and Cynthia Zanger, Fiber Optics: Communication and other Applications, Maxwell Macmillan Edition.

3) JC Palais, Fiber Optic Communications, 2nd Edition, PHI, 2001.

4) W.Tomasi, Advanced Electronic Communication Systems, Pearson Education, 2002

UNITI

OVERVIEWOFOPTICALFIBERCOMMUNICATION:INTRODUCTION

Introduction

Fiber-optic communication is a method of transmitting information from one place to another by sendingpulsesof lightthroughan opticalfiber. Thelightformsan electromagnetic carrier wavethat ismodulatedto carry information.[1]Fiber ispreferred over electrical cablingwhen highbandwidth, long distance, or immunity to electromagnetic interference are required. This type of communication can transmit voice, video, and telemetry through local area networks, computer networks, or across long distances.

Optical fiber is used by many telecommunications companies to transmit telephone signals, Internet communication,andcable television signals.Researchersat Bell Labshave reachedinternet speedsof over 100 peta bit ×kilometer per second using fiber-optic communication.

Theprocessofcommunicatingusingfiber-opticsinvolvesthefollowingbasicsteps:

1. creatingtheopticalsignalinvolvingtheuseofatransmitter,usuallyfromanelectrical signal
2. relaying the signal along the fiber, ensuring that the signal does not become too distorted or weak
3. receivingtheoptical signal
4. convertingitintoanelectrical signal

HistoricalDevelopment

First developed in the 1970s, fiber-optics have revolutionized the telecommunicationsindustry and have played a major role in the advent of the Information Age. Because of itsadvantages over electrical transmission, optical fibers have largely replaced copper wire communications in core networks in the developed world.

In1880AlexanderGrahamBell andhisassistant CharlesSumnerTainter createdaveryearly precursor to fiber-optic communications, the Photophone, at Bell's newly established Volta Laboratoryin Washington, D.C. Bell considered it his most important invention. The device allowedfor thetransmission of sound on a beam of light. On June 3, 1880, Bell conducted the world's first wirelesstelephonetransmission between two buildings, some 213 meters apart.[4][5]Due to its use of an atmospheric transmission medium, the Photophone would not prove practical until advances in laser and optical fiber technologies permitted the secure transport of light. The Photophone's first practical use came in military communication systems many decades later.

In 1954 Harold HopkinsandNarinder Singh Kapany showed that rolled fiber glass allowed light to be transmitted. Initially it was considered that the light can traverse in only straight medium. Jun-ichi Nishizawa, a Japanese scientist at Tohoku University, proposed the use of optical fibers for communications in1963. Nishizawa inventedthe PINdiode andthe static inductiontransistor, both of which contributed to the development of optical fiber communications.

In1966CharlesK.Kaoand GeorgeHockham atSTCLaboratories(STL)showedthatthelossesof 1,000dB/km in existing glass (compared to 5–10dB/km in coaxial cable) were due to contaminants which could potentially be removed.

Optical fiber was successfully developed in 1970 by Corning Glass Works, with attenuation lowenough for communication purposes (about 20 dB/km) and at the same time GaAssemiconductor lasers were developed that were compact and therefore suitable for transmitting light through fiber optic cables for long distances.

In 1973, Optelecom, Inc., co-founded by the inventor of the laser, Gordon Gould, received a contract from APA for the first optical communication systems. Developed for Army Missile Command in Huntsville, Alabama, it was a laser on the ground and a spout of optical fiber played out by missile to transmit a modulated signal over five kilometers.

Afteraperiod ofresearch startingfrom1975, thefirst commercialfiber-opticcommunicationssystem was developed which operated at a wavelength around 0.8 µm and used GaAs semiconductor lasers. This first-generation system operated at a bit rate of 45 Mbit/s with repeater spacing of up to 10 km. Soon on 22 April 1977, General Telephone and Electronics sent the first live telephone traffic through fiber optics at a 6 Mbit/s throughput in Long Beach, California.

In October 1973, Corning Glass signed a development contract with CSELT andPirelliaimed to test fiber optics in an urban environment: in September 1977, the second cable in this test series, named COS-2, was experimentally deployed in two lines (9 km) inTurin, for the first time in a big city, at a speed of 140 Mbit/s.

The second generation of fiber-optic communication was developed for commercial use in the early 1980s, operated at 1.3 µm and used InGaAsP semiconductor lasers. These early systems were initially limited by multi mode fiber dispersion, and in 1981 the single-mode fiberwas revealed to greatly improve system performance, however practical connectors capable of working with single mode fiber proved difficult to develop. Canadian service provider SaskTel had completed construction of whatwasthentheworld'slongestcommercialfiberopticnetwork,whichcovered3,268 km (2,031 mi) and linked 52 communities.[11]By 1987, these systems were operating at bit rates of up to 1.7Gb/swithrepeater spacingupto50km(31mi).

The firsttransatlantic telephone cable to use optical fiber wasTAT-8, based on Desurvireoptimised laser amplification technology. It went into operation in 1988.

Third-generation fiber-optic systems operated at 1.55 µm and had losses of about 0.2 dB/km. This development was spurred by the discovery of Indium gallium arsenideand the development of the Indium Gallium Arsenide photodiode by Pearsall. Engineers overcame earlier difficulties with pulse-spreading at that wavelength using conventional InGaAsP semiconductor lasers. Scientists overcame this difficulty by using dispersion-shifted fibersdesigned to have minimal dispersion at 1.55 µm or by limiting the laser spectrum to a single longitudinal mode.

Thesedevelopmentseventuallyallowedthird-generationsystemstooperatecommerciallyat 2.5Gbit/swithrepeaterspacinginexcessof100km(62mi).

The fourth generation of fiber-optic communication systems used optical amplification to reduce the need for repeaters and wavelength-division multiplexing to increasedata capacity. These two improvements caused a revolution that resulted in the doubling of system capacity every six months starting in 1992 until a bit rate of 10 Tb/s was reached by 2001. In 2006 a bit-rate of 14 Tbit/s was reached over a single 160 km (99 mi) line using optical amplifiers.

The focus of development for the fifth generation of fiber-optic communications is on extending the wavelength range over which a WDMsystem can operate. The conventional wavelength window, knownastheCband,coversthewavelengthrange1.53–1.57µm,and *dryfiber*hasalow-loss window promising an extension of that range to 1.30–1.65µm. Other developments include the concept of "optical solutions", pulses that preserve their shape by counteracting the effects of dispersion with the nonlinear effects of the fiber by using pulses of a specific shape.

In the late 1990s through 2000, industry promoters, and research companies such as KMI, and RHK predictedmassiveincreasesindemandforcommunicationsbandwidthduetoincreaseduseof theInternet, and commercialization of various bandwidth-intensive consumer services, such as video on demand.Internet protocol data traffic was increasing exponentially, at a faster rate thanintegratedcircuitcomplexityhadincreasedunder Moore'sLaw.Fromthebustofthedot-com bubblethrough2006,however,themaintrendintheindustryhasbeen consolidationoffirms andoffshoringof manufacturing to reduce costs. Companies such as Verizon andAT&Thave taken advantage of fiber-optic communications to deliver a variety of high-throughput data and broadband services to consumers' homes.

AdvantagesofFiberOptic Transmission

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

Extremely High Bandwidth: No other cable-based data transmission medium offers the bandwidth that fiber does. The volume of data that fiber optic cables transmit per unit time is far great than copper cables.

Longer Distance: in fiber optic transmission, optical cables are capable of providing low power loss, which enables signals can be transmitted to a longer distance than copper cables.

Resistance to Electromagnetic Interference: in practical cable deployment, it's inevitable to meet environments like power substations, heating, ventilating and other industrial sources ofinterference. However, fiber has a very low rate of bit error (10 EXP-13), as a result of fiber being so resistant to electromagnetic interference. Fiber optic transmission is virtually noise free.

Low Security Risk: the growth of the fiber optic communication market is mainly driven by increasing awareness about data security concerns and use of the alternative raw material. Data or signals are transmitted via light in fiber optic transmission. Therefore there is no way to detect the data being transmitted by "listening in" to the electromagnetic energy "leaking" through the cable, whichensures the absolute security of information.

Small Size: fiber optic cable has a very small diameter. For instance, the cable diameter of a single OM3 multimode fiber is about 2mm, which is smaller than that of coaxial copper cable. Small size saves more space in fiber optic transmission.

Light Weight: fiber optic cables are made of glass or plastic, and they are thinner than copper cables. These make them lighter and easy to install.

Easy to Accommodate Increasing Bandwidth: with the use of fiber optic cable, new equipment canbe added to existing cable infrastructure. Because optical cable can provide vastly expanded capacity overtheoriginallylaidcable.AndWDM(wavelengthdivisionmultiplexing)technology, including CWDM and DWDM, enables fiber cables the ability to accommodate more bandwidth.

DisadvantagesofFiberOpticTransmission

Thoughfiberoptictransmissionbringslotsofconvenience,itsdisadvantagesalsocannotbe ignored.**Fragility:** usually optical fiber cables are made of glass, which lends to they are more fragile than electrical wires. In addition, glass can be affected by various chemicals including hydrogen gas (a problem in underwater cables), making them need more cares when deployed under ground.

Difficult to Install: it's not easy to splice fiber optic cable. And if you bend them too much, they will break. And fiber cable is highly susceptible to becoming cut or damaged during installation or construction activities. All these make it difficult to install.

Attenuation & Dispersion: as transmission distance getting longer, light will be attenuated and dispersed, which requires extra optical components like EDFA to be added.

Cost Is Higher Than Copper Cable: despite the fact that fiber optic installation costs are dropping byas much as 60% a year, installing fiber optic cabling is still relatively higher than copper cables. Because copper cable installation does not need extra care like fiber cables. However, optical fiber is still moving into the local loop, and through technologies such as FTTx (fiber to the home, premises, etc.) and PONs (passive optical networks), enabling subscriber and end user broadband access.

Special Equipment Is Often Required: to ensure the quality of fiber optic transmission, some special equipment is needed. For example, equipment such as OTDR(optical time-domain reflectometry) is required and expensive, specialized optical test equipment such as optical probes and power meter are needed at most fiber endpoints to properly provide testing of optical fiber.

ApplicationsofOpticalFiberCommunications

Fiberopticcablesfindmanyusesinawidevarietyofindustriesandapplications.Someusesof fiber optic cables include:

- **Medical**

  Usedaslightguides,imagingtoolsandalsoaslasersforsurgeries

- **Defense/Government**

  Used ashydrophonesforseismicwavesandSONAR,aswiringinaircraft,submarinesandother vehicles and also for field networking
- **Data Storage**

  Used fordatatransmission
- **Telecommunications**

  Fiberislaidandusedfortransmittingandreceivingpurposes
- **Networking**

  Used toconnectusersandserversinavarietyofnetworksettingsandhelpincreasethespeedand accuracy of data transmission
- **Industrial/Commercial**

  Used forimaginginhardtoreachareas,aswiringwhereEMIisanissue,assensorydevicesto make temperature, pressure and other measurements, and as wiring in automobiles and in industrial settings
- **Broadcast/CATV**

  Broadcast/cablecompaniesareusingfiberopticcablesforwiringCATV,HDTV,internet,videoon- demand and other applications

  Fiber optic cables are used for lighting and imaging and as sensors to measure and monitor a vast arrayofvariables.Fiberopticcablesarealsousedinresearchanddevelopmentandtestingacross all the above mentioned industries

Theopticalfibershavemanyapplications.Someofthemareasfollows−

- Usedintelephone systems
- Usedinsub-marinecable networks
- Usedindatalinkforcomputernetworks,CATVSystems
- UsedinCCTVsurveillance cameras
- Usedforconnectingfire,police,andotheremergencyservices.
- Usedinhospitals,schools,andtrafficmanagementsystems.
- Theyhavemanyindustrialusesandalsousedforinheavyduty constructions.

BlockDiagramofOpticalFiberCommunicationSystem

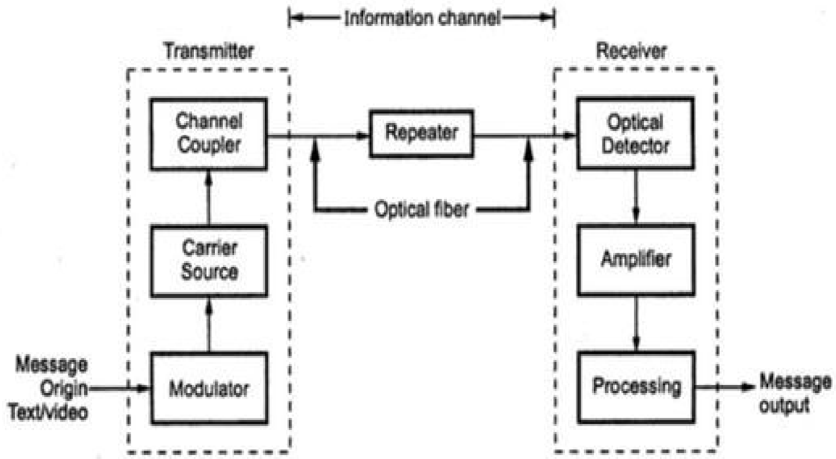

Fig1:BlockDiagramofOpticalFiberCommunicationSystem

Messageorigin:

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

Modulator:

Themodulatorhastwomainfunctions.

1) Itconvertstheelectricalmessageintoproperformat.

2) Itimpressesthissignalontothewavegeneratedbythecarriersource.

wodistinctcategoriesofmodulationareusedi.e.analogmodulationanddigital modulation.

Carriersource:

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

Channelcoupler:

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

Information channel:

. The information channel is the path between the transmitter and receiver. In fiber optic communications, a glass or plastic fiber is the channel. Desirable characteristics of the information channel include low attenuation and large light acceptance cone angle. Optical amplifiers boost the power levels of weak signals. Amplifiers are needed in very long links to provide sufficient power to the receiver. Repeaters can be used only for digital systems. They convert weak and distorted optical signals to electrical ones and then regenerate theoriginal 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 fiber optic frequencies and divides its power along several ray paths. This results in a distortion of the propagation 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.

Opticaldetector:

. The information begin transmitted is detected by detector. In the fiber system the optic wave is converted into an electric current by a photodetector. 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 photodetectors 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 syst5em decision circuit is an additional block. The bit error rate (BER) should be very small for quality communications.

Signalprocessing:

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Messageoutput:

. The electrical form of the message emerging from the signal processor is transformed into a sound waveor visual image. Sometimesthesesignalsare directlyusablewhen computersorothermachines are connected through a fiber system.

ElectromagneticSpectrum

Theradiowavesandlightareelectromagneticwaves.Therateatwhichtheyalternatein
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)

Infiberoptics,itismoreconvenienttousethewavelengthoflightinsteadofthefrequency withlight frequencies;wavelengthisoftenstatedinmicrons ornanometers. 1
micron (μ) = 1
Micrometre (1x10-6)1nano(n) =10-9meter
Fiber optics usesvisible and infrared light. Infrared light covers afairlywide range of wavelengthsand is generally used for all fiber optic communications. Visible light is normally used for very short range transmission using a plastic fiber.

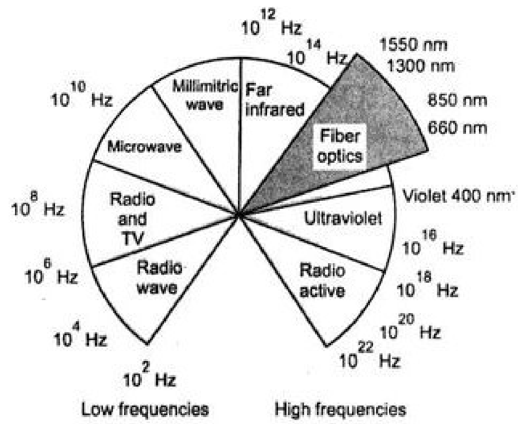
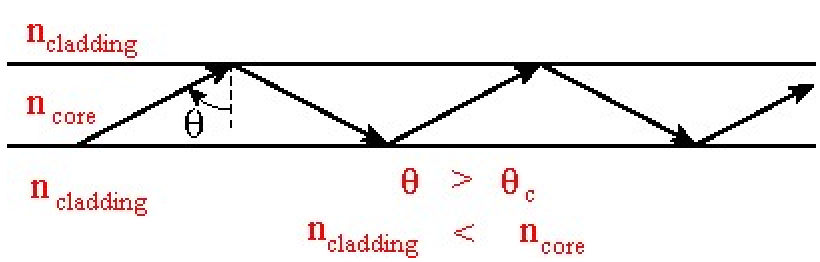


Fig2:Electromagnetic Spectrum

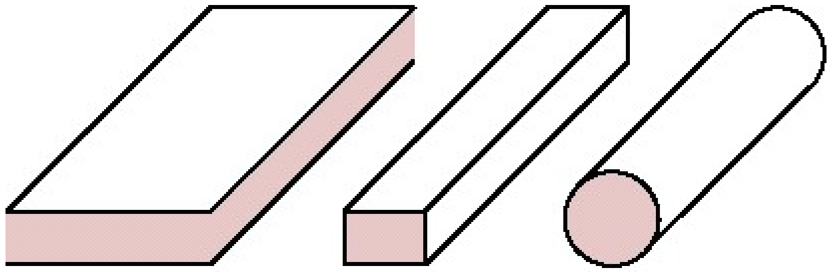
OpticalFiberWaveguides

In free spacelight ravelsas its maximumpossiblespeed i.e. 3 x108 m/sor 186 x 103 miles/sec. When light travels through a material it exhibits certain behavior explained by laws of reflection, refraction.

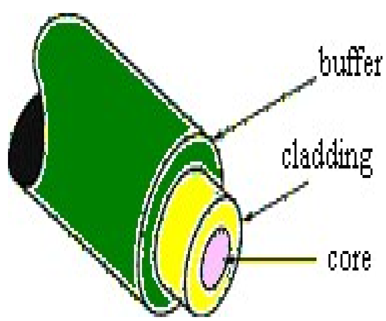
An optical wave guide is a structure that "guides" a light wave by constraining it to travel along acertain desired path.If thetransversedimensions of theguide are much larger than thewavelengthof the guided light, then we can explain how the optical waveguide works using geometrical optics and total internal reflection.



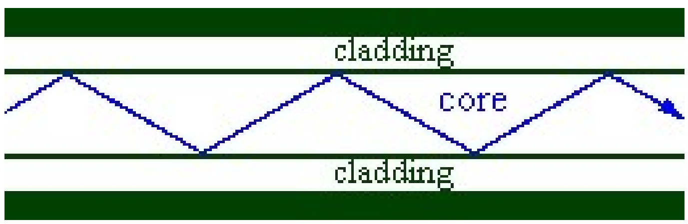
Awaveguidetrapslightbysurroundingaguidingregion,calledthecore,madefromamaterialwith index of refraction n_{core}, with a material called thecladding, made from a material with index of refraction $n_{cladding} < n_{core}$. Light entering is trapped as long as $\sin\theta > n_{cladding}/n_{ncore}$.



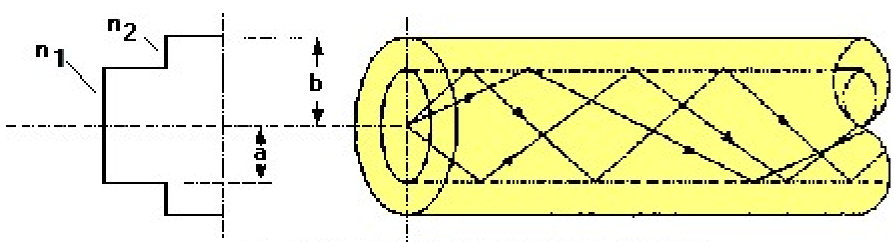
Light can be guided by planar or rectangular wave guides, or by optical fibers.An optical fiber consists ofthreeconcentricelements,thecore,thecladdingandtheoutercoating,oftencalledthe buffer.Thecoreisusuallymadeofglassorplastic.Thecoreisthelight-carryingportionofthe fiber.The cladding surrounds the core.The cladding is made of a material with a slightly lower index of refraction than the core.This difference in the indices causes total internal reflection to occur at the core-cladding boundary along the length of the fiber.Light is transmitted down the fiber anddoes not escape through the sides of the fiber.



- FiberOpticCore:
  - theinnerlight-carryingmemberwithahighindexof refraction.
- Cladding:
  - the middle layer, which serves to confine the light to the core.It has a lower index of refraction.

- Buffer:
    - the outer layer, which serves as a "shock absorber" to protect the core and cladding fromdamage.The coating usually comprises oneor more coats of a plastic materialto protect the fiber from the physical environment.Sometimes metallic sheaths are added to the coating for further physical protection.
    - 

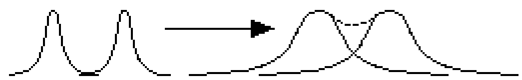
- Light injected into the fiber optic core and striking the core-to-cladding interface at an angle greaterthanthecriticalangleisreflectedbackintothecore.Sincetheanglesofincidenceand reflection are equal, the light ray continues to zigzag down the length of the fiber.The light is trapped within the core.Light striking the interface at less than the critical angle passes into the cladding and is lost.



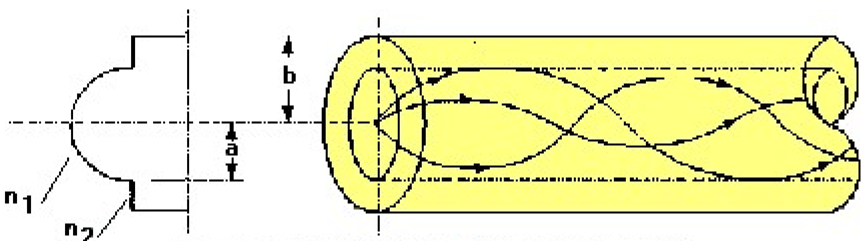
MULTIMODE STEP-INDEX FIBER

- Fibers for which the refractive index of the core is a constant and the index changes abruptlyat the core-cladding interface are called step-index fibers. Step-index fibers are available with core diameters of 100 mm to 1000 mm.They are well suited to applications requiring high-power densities, such as delivering laser power for medical and industrial applications.

- Multimode step-index fiberstrap light with many different entrance angles, each mode in a step-index multimode fiber is associated with a different entrance angle.Each modetherefore travels along a different path through the fiber.Different propagating modes have different velocities.As an optical pulse travels down a multimode fiber, the pulse begins to spread.Pulsesthatenterwellseparatedfromeachotherwilleventuallyoverlapeach other.This limits the distance over which the fiber can transport data.Multimode step-index fibers are not well suited for data transport and communications.

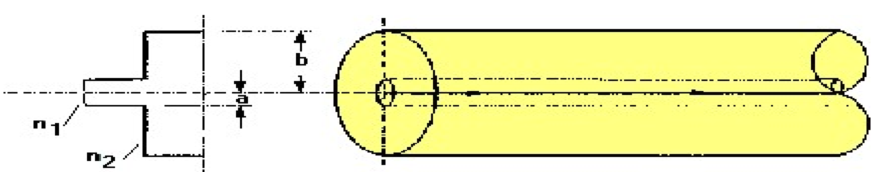
- 

- In amultimode graded-index fiberthe core has an index of refraction that decreases as the radial distance from the center of the core increases.As a result, the light travels faster near the edge of the core than near the center.Different modes therefore travel in curved paths with nearly equal travel times.This greatly reduces the spreading of optical pulses.



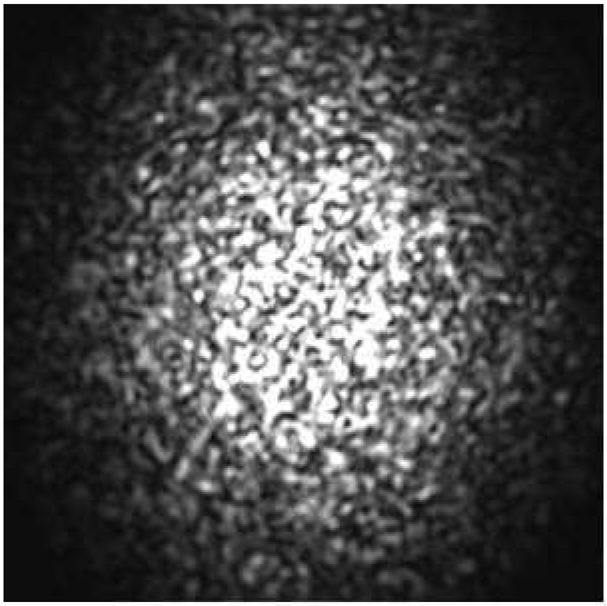
MULTIMODE GRADED-INDEX FIBER

-
- A **single mode fiber** only allows light to propagate down its center and there are no longer differentvelocitiesfordifferentmodes.Asinglemodefiberismuchthinnerthan amultimode fiber and can no longer be analyzed using geometrical optics.Typical core diameters are between 5 mm and 10 mm.

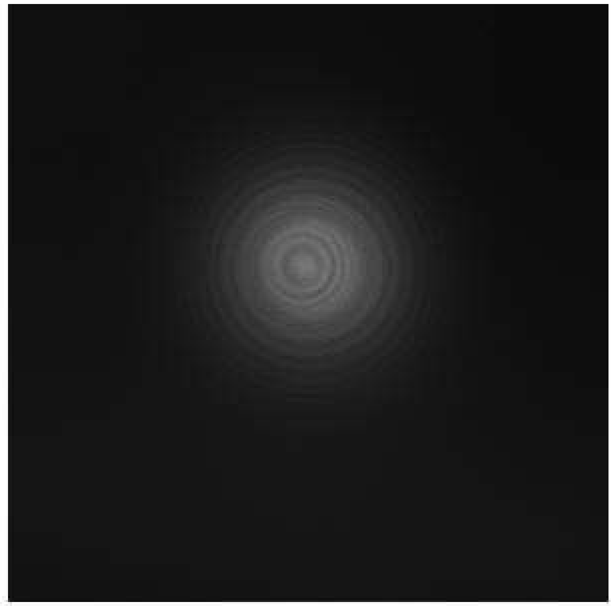


SINGLE MODE STEP-INDEX FIBER

When laser light is coupled into a fiber, the distribution of the light emerging from the other end reveals if the fiber is a multimode or single mode fiber.



Light emerging from a multi-mode fiber

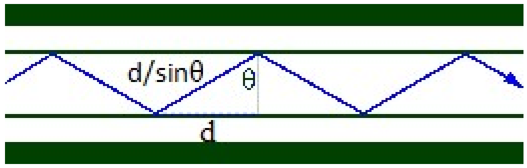


Light emerging from a single-mode fiber

Optical fibers are used widely in the medical field for diagnoses and treatment.Optical fibers can be bundled into flexible strands, which can be inserted into blood vessels, lungs and other parts of the body.An Endoscope is a medical tool carrying two bundles of optic fibers inside one long tube.One bundle directs light at the tissue being tested, while the other bundle carries light reflected from the tissue, producing a detailed image.Endoscopes can be designed to look at regions of the human body, such as theknees, or other joints in the body

Problem:

In a step-index fiber in the ray approximation, the ray propagating along the axis of the fiber has the shortest route, while the ray incident at the critical angle has the longest route.Determine the difference in travel time(in ns/km)for the modes defined bythose two rays for afiber with n_{core}= 1.5 and $n_{cladding}$= 1.485.



Solution:

Ifaraypropagatingalongtheaxisofthefibertravelsadistanced,thenarayincidentatthecritical angle$\theta_c$travelsadistanceL=d/sinθ_c.
Therespectivetraveltimesaret_d=dn_{core}/candt_L= dn_{core}/(sinθ_cc).
sinθ_c= $n_{cladding}$/n_{core}.

θ_c=81.9deg.
Ford=1000mwehavet_d=5000nsandt_L=5050.51ns. The

difference in travel time is therefore 50.51 ns/km. **Ray**

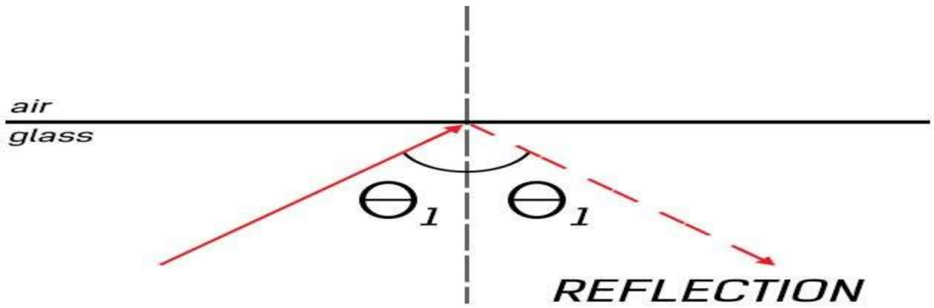
theory

Thephenomenonofsplittingofwhitelightintoitsconstituentsisknownasdispersion.Theconcepts of reflection and refraction of light are based on a theory known as Ray theory or geometric optics,where light waves are considered as waves and represented with simple geometric lines or rays.

Thebasiclawsofraytheory/geometric optics

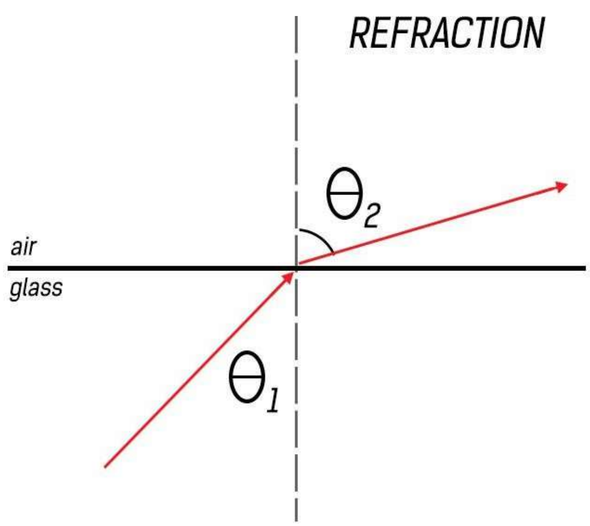
- Inahomogeneousmedium,lightraysarestraight lines.
- Lightmaybeabsorbedorreflected
- Reflected ray lies in the plane of incidence and angle of incidence will be equal to the angle of reflection.

- At the boundary between two media of different refractive indices, the refracted ray will lie in the plane of incidence. Snell's Law will give the relationship between the angles of incidence and refraction.



Reflection depends on the type of surface on which light is incident. An essential condition for reflection to occur with glossy surfaces is that the angle made by the incident ray of light with the normal at the point of contact should be equal to the angle of reflection with that normal.

The *images*produced from this reflection have different properties according to the shape of the surface. For example, for a flat mirror,the image produced is upright, hasthe same size as that of the object and is equally distanced from the surface of the mirror as the real object. However, the properties of a parabolic mirror are different and so on.



Refraction isthebendingoflightinaparticularmediumduetothe speedof lightinthat medium. The speedoflightinanymediumcanbegivenby

$$v = \frac{c}{n}$$

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

The refractive index for vacuum and air os 1.0 for water it is 1.3 and for glass refractive index is 1.5. Here n is the**refractive index** of that medium. When a ray of light is incident at the interface of two mediawithdifferentrefractiveindices,itwillbendeithertowardsorawayfromthenormal depending on the refractive indices of the media.

Accordingto**Snell'slaw**,refractioncanberepresentedas

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

n_1=refractiveindexoffirstmedium θ_1=

angle of incidence

n_2= refractiveindex of secondmedium

θ_2= angle of refraction

For$n_1 > n_2$,$\theta_2$isalwaysgreaterthanθ_1.**Or**toput it indifferentwords,lightmovingfrom a medium of high refractive index (glass) to a medium of lower refractive index (air) will move away from the normal.

Totalinternalreflection

To consider the propagation of light within an optical fiber utilizing the ray theory model it is necessary to take account of the refractive index of the dielectric medium. Optical materials are characterized bytheir index of refraction, referred to as n.The refractive index of amedium isdefined as the ratio of the velocity of light in a vacuum to the velocity of light in the medium.

When a beam of light passes from one material to another with a different index of refraction, the beam is bent (or refracted) at the interface (Figure 2).

$$n_I \sin I = n_R \sin R$$

where $n_I$andn_R aretheindicesofrefractionofthematerialsthroughwhichthebeamisrefracted and *I*and *R*are the angles of incidence and refraction of the beam. If the angle of incidence is greater than the critical angle for the interface (typically about 82° for optical fibers), the light is reflectedback into the incident medium without loss by a process known as total internal reflection (Figure 3).

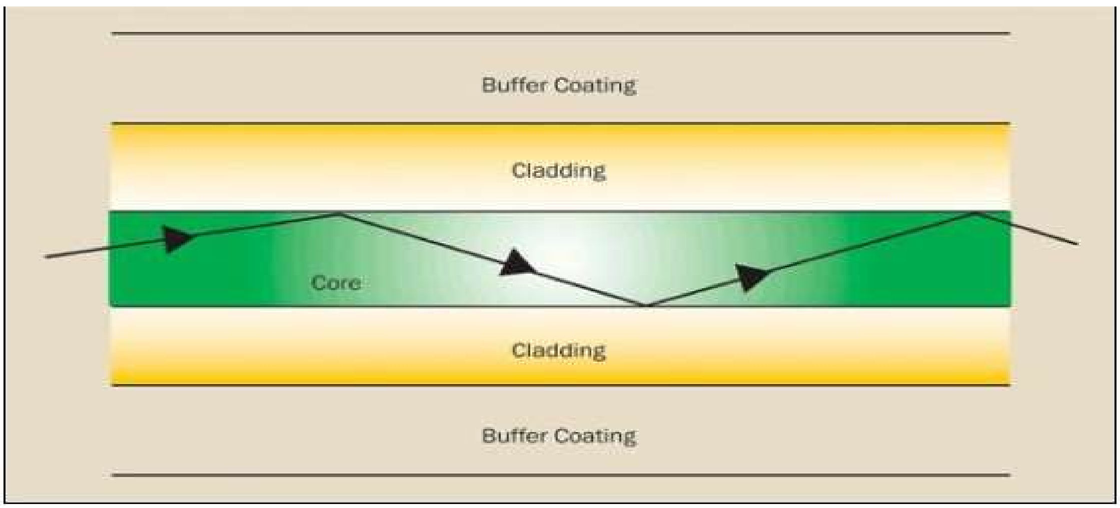


Figure 3. *Total internal reflection allows light to remain inside the core of the fiber.*

RefractionisdescribedbySnell'slaw:

A ray of light travels more slowly in an optically dense medium than in one that is less dense, and the refractive index gives a measure of this effect. When a ray is incident on the interface between two dielectrics of differing refractive indices (e.g. glass–air), refraction occurs, as illustrated in Figure 1.2(a). It may be observed that the ray approaching the interface is propagating in a dielectric of refractive index *n* and is at an angle ϕ to the normal at the surface of the interface.

If the dielectric on the other side of the interface has a refractive index *n* which is less than *n*1, then the refraction is such that the raypath in this lower indexmediumis at an angleto the normal,where is greater than . The angles of incidenceand refractionare related to each other and to therefractive indices of the dielectrics by Snell's law of refraction, which states that:

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

Or

$$\frac{\sin \phi_1}{\sin \phi_2} = \frac{n_2}{n_1}$$

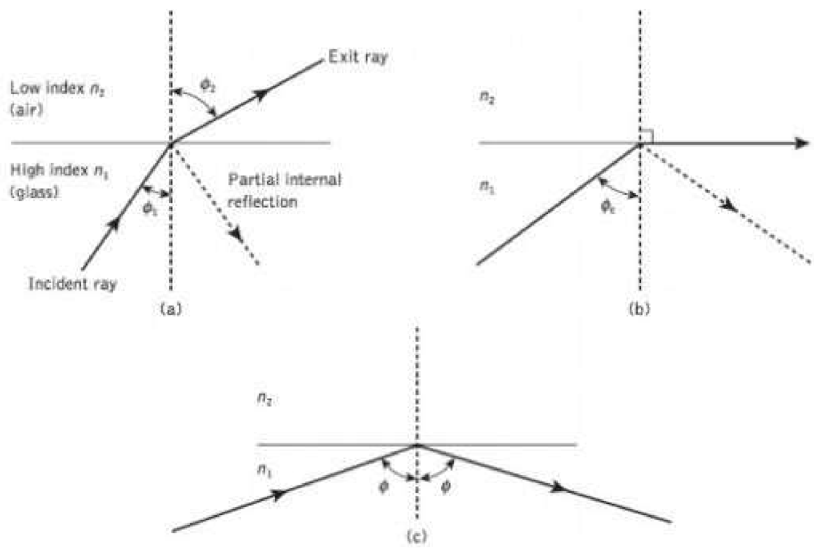


Figure 1.2 Light rays incident on a high to low refractive index interface (e.g. glass air): (a) refraction; (b) the limiting case of refraction showing the critical ray at an angle φ_c (c) total internal reflection where $\varphi > \varphi_c$

It may also be observed in Figure 1.2(a) that a small amount of light is reflected back into the originating dielectric medium (partial internal reflection). As*n* is greater than *n*, the angle of refraction is always greater than the angle of incidence. Thus when the angle of refraction is 90° and the refracted ray emerges parallel to the interface between the dielectrics, the angle of incidence must be less than 90°.

Thisisthelimitingcaseofrefractionandtheangleofincidenceisnowknownasthecriticalangleϕc, asshowninFigure1.2(b).FromEq.(1.1)thevalueofthecriticalangleisgivenby

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

At angles of incidence greater than the critical angle the light is reflected back into the originating dielectric medium (total internal reflection) with high efficiency (around 99.9%). Hence, it may be observed in Figure 1.2(c) that total internal reflection occurs at the inter- face between twodielectrics of differing refractive indices when light is incident on the dielectric of lower index fromthe dielectric of higher index, and the angle of incidence of the ray exceeds the critical value. This is the mechanism by which light at a sufficiently shallow angle (less than 90° − may be considered to propagate down an optical fiber with low loss.

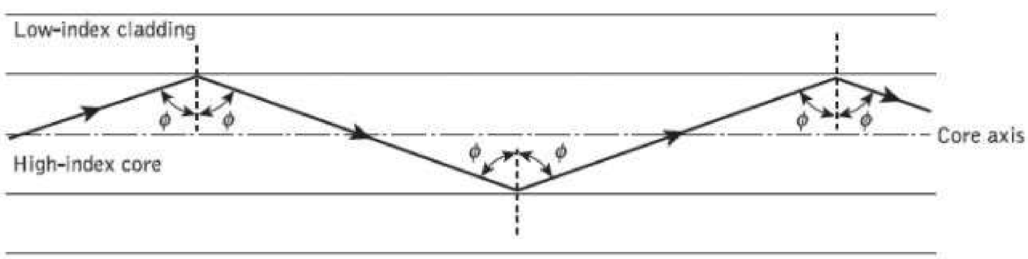


Figure 1.3 The transmission of a light ray in a perfect optical fiber

Figure 1.3 illustrates the transmission of a light ray in an optical fiber via a series of total internal reflections at the interface of the silica core and the slightly lower refractive index silica cladding. The ray hasan angle of incidence ϕat the interfacewhich is greaterthan the critical angle and isreflected at the same angle to the normal.

The light ray shown in Figure 1.3 is known asameridional ray asit passesthrough the axis of the fiber core. This type of ray is the simplest to describe and is generally used when illustrating the fundamental transmission properties of optical fibers. It must also be noted that the lighttransmission illustrated in Figure 1.3 assumes a perfect fiber, and that any discontinuities or imperfections at the core–cladding interface would probably result in refraction rather than total internal reflection, with the subsequent loss of the light ray into the cladding.

CriticalAngle

When the angle of incidence (ϕ_1) is progressively increased, there will be progressive increase ofrefractiveangle(ϕ_2).Atsomecondition(ϕ_1)therefractiveangle(ϕ_2)becomes90^otothenormal.Whenthis happenstherefractedlightraytravelsalongthe interface.Theangleofincidence(ϕ_1)atthepoint atwhichthe refractive angle (ϕ_1) becomes 90^O is called the critical angle. It is denoted by ϕ_c.

The **critical angle** is defined as the minimum angle of incidence (ϕ_1) at which the ray strikes the interface of two media and causes an angle of refraction (ϕ_2) equal to 90^O. Fig 1.6.5 shows critical angle refraction. When the angle of refraction is 90 degree to the normal the refracted ray is parallel to the interface between the two media.

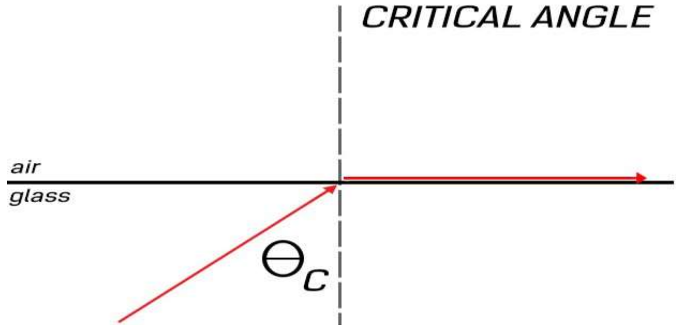
Henceatcriticalangle$\phi_1 = \phi_c$and$\phi_2 = 90^O$

UsingSnell'slaw:$n_1 \sin\phi_1 = n_2 \sin\phi_2$

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

$$\because \quad \sin 90^o = 1$$

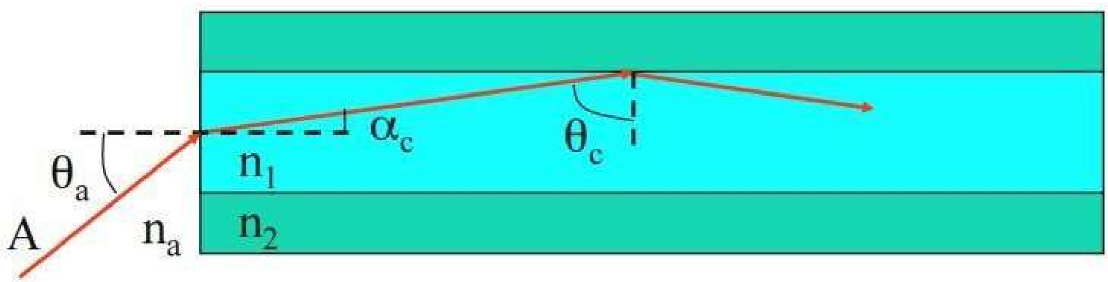
$$\boxed{\text{Critical angle } \phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)}$$



Itisimportanttoknowaboutthispropertybecausereflectionisalsopossibleevenifthesurfaces arenot reflective. If the*angle of incidence is greater than the critical angle* for a given setting, the resulting type of reflection is called **Total Internal Reflection**, and it is the basis of Optical Fiber Communication.

Acceptanceangle

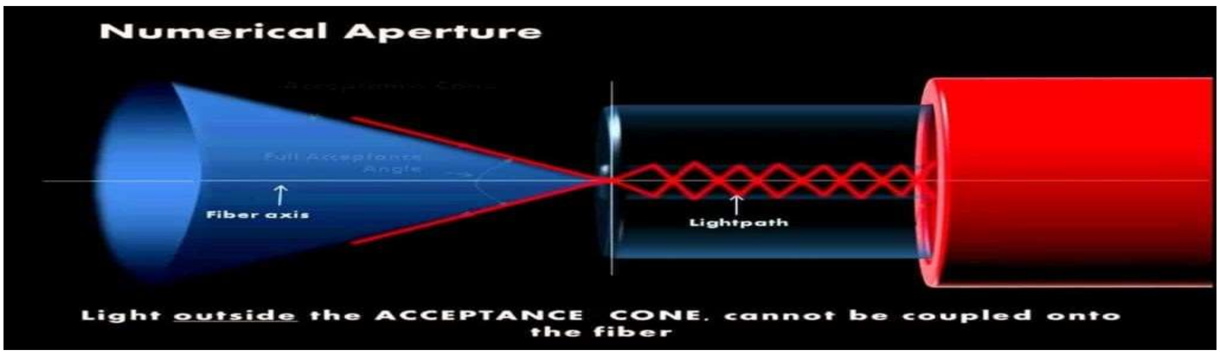
In an opticalfiber,a lightray undergoesits*first refraction*at the air-coreinterface.The angleat which thisrefractionoccursiscrucialbecausethisparticularanglewilldictatewhetherthe subsequent *internal* reflections will follow the principle of Total Internal Reflection. This angle, at which the light ray first encounters the core of an optical fiber is called Acceptance angle.



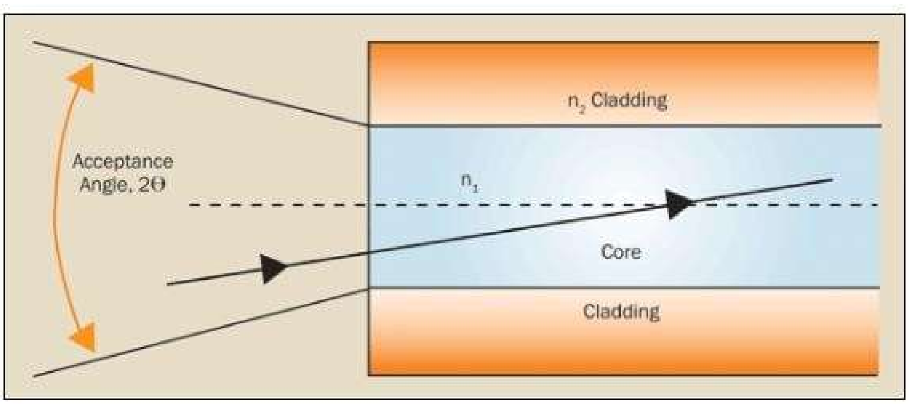
The objective is to have [latex] \theta_{c}[/latex] greater than the critical angle for this particular setting. As you can notice, $\theta_c$depends on the orientation of the refracted ray at the input of the optical fiber. This in turn depends onθ_a, the acceptance angle. Theacceptanceanglecanbecalculatedwiththehelpoftheformulabelow.

NumericalAperture

Numerical Aperture is a characteristic of any optical system. For example, photo-detector, optical fiber, lenses etc. are all optical systems. Numerical aperture is the ability of the optical system to collect all of the light incident on it, in one area.



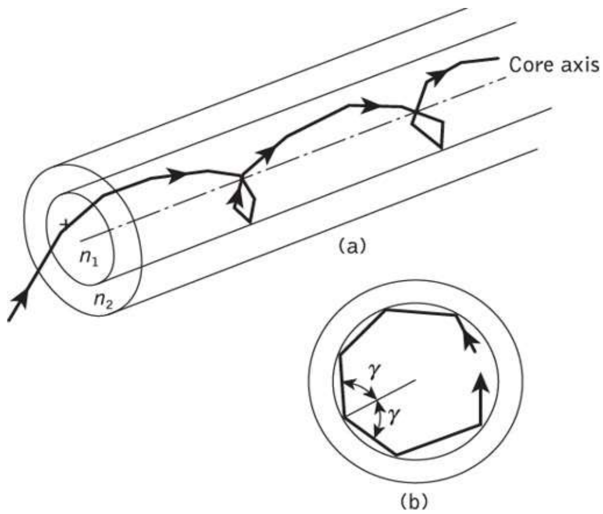
The blue cone is known as the cone of acceptance. As you can see it is dependent on the Acceptance Angle of the optical fiber. Light waves within the acceptance cone can be collected in a small area which can then be sent into the optical fiber (Source)



Numericalaperture(NA),showninaboveFigure,isthe measureofmaximumangleatwhichlightrays will enter and be conducted down the fiber. This is represented by the following equation:

$$NA = \sqrt{(n^2_{core} - n^2_{cladding})} = \sin\theta$$

skew rays: In amultimode optical fiber, a bound raythat travels in a helical path along the fiber and thus (a) is not parallel to the fiber axis, (b) does not lie in a meridional plane, and (c) doesnot intersect the fiber axis is known as a Skew Ray.



1. Skewraysareraysthattravelthroughanopticalfiberwithoutpassingthroughitsaxis.
2. A possible path of propagation of skew rays is shown in figure. Figure 24, view (a), provides an angled view and view (b) provides a front view.

3. Skew raysarethoserays whichfollowhelicalpathbuttheyarenot confined toa singleplane.Skew rays are not confined to a particular plane so they cannot be tracked easily. Analyzing the meridional rays is sufficient for the purpose of result, rather than skew rays, because skew rays lead to greater power loss.

4. Skew rays propagate without passing throughthe center axis of the fiber. The acceptance angle for skew rays is larger than the acceptance angle of meridional rays.

5. Skew rays are often used in the calculation of light acceptance in an optical fiber. The addition of skew rays increases the amount of light capacity of a fiber. In large NA fibers, the increase may be significant.

6. The addition of skew rays also increases the amount of loss in a fiber. Skew rays tend to propagate near the edge of the fiber core. A large portion of the number of skew rays that are trapped in the fiber core are considered to be leaky rays.

7. Leaky rays are predicted to be totally reflected at the core-cladding boundary. However, these rays are partially refracted because of the curved nature of the fiber boundary. Mode theory is also usedto describe this type of leaky ray loss.

Cylindricalfiber

1. Modes

When light is guided down a fiber (as microwaves are guided down a waveguide), phase shifts occur atevery reflectiveboundary. Thereis afinitediscretenumber ofpathsdowntheopticalfiber (known as modes) that produce constructive (in phase and therefore additive) phase shifts that reinforce the transmission. Because each mode occurs at a different angle to the fiber axis as the beam travels along the length, each one travels a different length through the fiber from the input to the output. Only one mode, the zero-order mode, travels the length of the fiber without reflections from the sidewalls. This is known as a single-mode fiber. The actual number of modes that can be propagated in a given optical fiber is determined by the wavelength of light and the diameter and index of refraction of the core of the fiber.

The exact solution of Maxwell's equations for a cylindrical homogeneous core dielectric waveguide* involves much algebra and yields a complex result. Although the presentation of this mathematics is beyond the scope of this text, it is useful to consider the resulting modal fields. In common with the planar guide (Section 1.3.2), 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 thanone. 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 tomeridionalrays(seeSection1.2.1)travelingwithinthefiber.However,hybridmodes where E_z and H_z are nonzero also occur within the cylindrical waveguide.

These modes, which result from skew ray propagation (see Section 1.2.4) 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.

Fortunately, the analysis may be simplified when considering optical fibers for communication purposes. These fibers satisfy the weakly guiding approximation where the relative index difference Δ1. This corresponds to small grazing angles θ in Eq. (1.34). In fact is usually less than 0.03 (3%) for optical communications fibers. For weakly guiding structures with dominant forward propagation, mode theory gives dominant transverse field components. Hence approximate solutions for the full set of HE, EH, TE and TM modes may be given by two linearly polarized components.

These linearly polarized (LP) modes are not exact modes of the fiber except for the fundamental (lowest order) mode. However, as in weakly guiding fibers is very small, then HE– EH mode pairsoccur which have almost identical propagation constants. Such modes are said to be degenerate. The superpositions of these degenerating modes characterized by a common propagation constant correspondto particularLP modesregardlessoftheir HE, EH,TEor TM field configurations.Thislinear combination of degenerate modes obtained from the exact solution produces a useful simplification in the analysis of weakly guiding fibers.

The relationship between the traditional HE, EH, TE and TM mode designations and the LP*lm* mode designations is shown in Table 1.1. The mode subscripts *l*and *m*are related to the electric field intensity profile for a particular LP mode (see Figure 1.11(d)). There are in general 2*l*field maxima around the circumference of the fiber core and *m*field maxima along a radius vector. Furthermore, it may be observed from Table 1.1 that the notation for labeling the HE and EH modes has changedfrom that specified for the exact solution in the cylindrical waveguide mentioned previously.

Table 1.1 Correspondence between the lower order in linearly polarized modes and the traditional exact modes from which they are formed

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)	$HE_{l+1,m}$, $EH_{l-1,m}$

2. Modecoupling

We have thus far considered the propagation aspects of perfect dielectric waveguides. However, 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 1.13, which illustrates two types of perturbation. It may beobserved that in both cases the ray no longer maintains the same angle with the axis. In electromagnetic wave theory this corresponds to a change in the propagating mode for the light.Thus individual modes do not normally propagate throughout the length of the fiber without large energy transfers to adjacent modes, even when the fiber is exceptionally good quality and is not strained or bent by its surroundings. This mode conversion is known as mode coupling or mixing. It is usually analyzed using coupled mode equations which can be obtained directly from Maxwell’s equations.

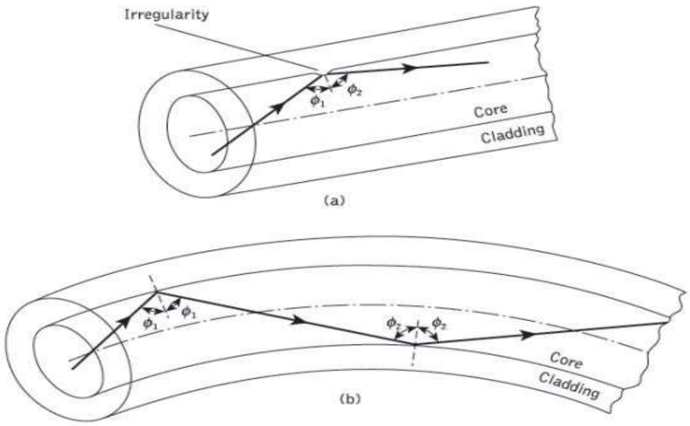


Figure 1.13 *Ray theory illustrations showing two of the possible fiber perturbations which give mode coupling: (a) irregularity at the core–cladding interface; (b) fiber bend*

3. Stepindexfibers

The optical fiber considered in the preceding sections with a core of constant refractive index *n*1and a cladding of a slightly lower refractive index *n*2is known as step index fiber. This is because the refractive index profile for this type of fiber makes a step change at the core–cladding interface, as indicated in Figure 1.14, which illustrates the two major types of step index fiber.The refractive index profile may be defined as

$$n(r) = \begin{cases} n_1 & r < a \quad \text{(core)} \\ n_2 & r \geq a \quad \text{(cladding)} \end{cases} \tag{1.48}$$

in both cases.

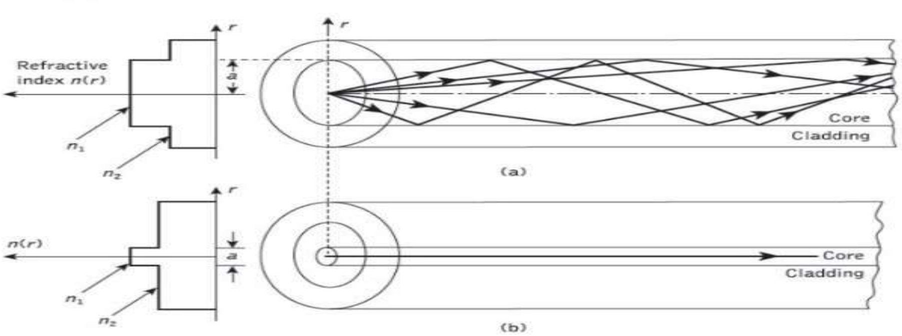


Figure 1.14 The refractive index profile and ray transmission in step index fibers: (a) multimode step index fiber; (b) single-mode step index fiber

Figure 1.14(a) shows a multimode step index fiber with a core diameter of around 50μm or greater, whichislargeenoughtoallowthepropagationofmanymodeswithinthefibercore.Thisis illustrated in Figure 1.14(a) by the many different possible ray paths through the fiber. Figure 1.14(b) shows a single-mode or monomode step index fiber which allows the propagation of only one transverse electromagnetic mode (typically HE11), and hence the core diameter must be of the order of 2 to 10μm. The propagation of a single mode is illustrated in Figure 1.14(b) as corresponding to a singleray path only (usually shown as the axial ray) through the fiber.

The single-mode step indexfiber has the distinct advantage of low intermodal dispersion (broadening of transmitted light pulses), as only one mode is transmitted, whereas with multimode step index fiber considerable dispersion may occur due to the differing group velocities of the propagating modes. This in turn restricts the maximum bandwidth attainable with multimode step index fibers, especially when com- pared with single-mode fibers.

However, for lower bandwidth applications multimode fibers have several advantages over single-mode fibers. These are:

a) The use of spatially incoherent optical sources (e.g. most light-emitting diodes) which cannot be efficiently coupled to single-mode fibers.

b) Largernumericalapertures,aswellascorediameters,facilitatingeasiercouplingtooptical sources

c) Lowertolerancerequirementsonfiber connectors

Multimode step index fibers allow the propagation of a finite number of guided modes along the channel. The number of guided modes is dependent upon the physical parameters (i.e. relative refractive index difference, core radius) of the fiber and the wavelengths of the transmitted light which are included in the normalized frequency *V* for the fiber.

Mode propagation does not entirely cease below cutoff. Modes may propagate as unguided or leaky modes which can travel considerable distances along the fiber. Nevertheless, it is the guided modes which are of paramount importance in optical fiber communications as these are confined to thefiber over its full length. that the total number of guided modes or mode volume *M*sfor a step index fiber is related to the *V* value for the

fiberbytheapproximateexpression

Which allows an estimate of the number of guided modes propagating in a particular multimode step index fiber.

4. Gradedindex fibers

Gradedindexfibersdonothaveaconstantrefractiveindexinthecore*butadecreasingcore index $n(r)$ with radial distance from a maximum value of$n1$ at the axis to a constant value $n2$beyond the core radius a in the cladding. This index variation may be represented as:

$$n(r) = \begin{cases} n_1(1 - 2\Delta(r/a)^{\alpha})^{\frac{1}{2}} & r < a \quad \text{(core)} \\ n_1(1 - 2\Delta)^{\frac{1}{2}} = n_2 & r \geq a \quad \text{(cladding)} \end{cases} \qquad (1.50)$$

wherei the relative refractive index difference and α is the profile parameter which gives the characteristic refractive index profile of the fiber core. Equation (1.50) which is a convenient method of expressing the refractive index profile of the fiber core as a variation of α, allows representation of the step index profile when α = ∞, a parabolic profile when α = 2 and a triangular profile when α = 1. This range of refractive index profiles is illustrated in Figure 1.15

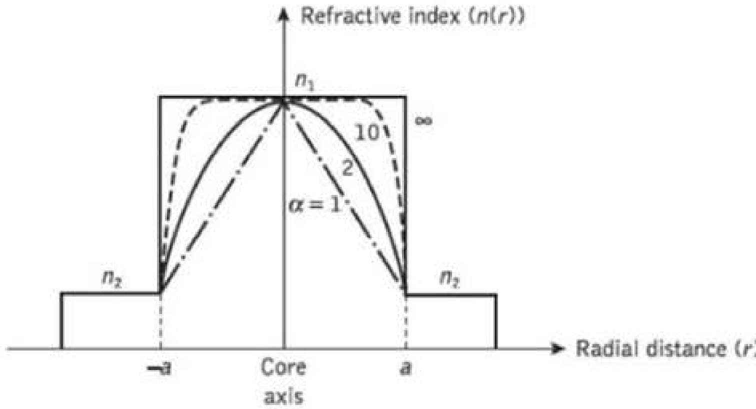


Figure 1.15 Possible fiber refractive index profiles for different values of α (given in Eq. (1.50)

The graded index profiles which at present produce the best results for multimode optical propagationhaveanearparabolicrefractiveindexprofilecorewith~~2.Fiberswithsuchcore index profiles are well established and consequently when the term 'graded index' is used without qualification it usually refers to a fiber with this profile.

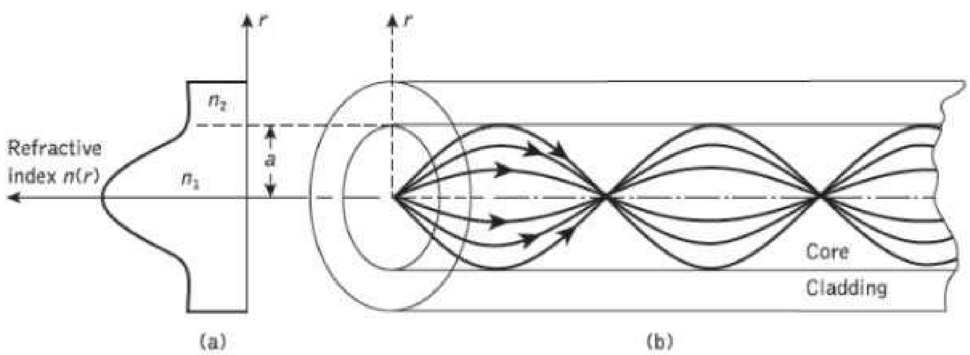


Figure 1.16 The refractive index profile and ray transmission in a multimode graded index fiber

Where r=Radialdistancefromfiberaxis

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

a=Core radius

n_1=Refractiveindexofcore

n_2=Refractiveindexof
cladding α = Shape of
index profile.

Profileparameterαdeterminesthecharacteristicrefractiveindexprofileoffibercore.

For this reason in this section we consider the waveguiding properties of graded index fiber with a parabolic refractive index profile core.A multimode graded index fiber with a parabolic index profile core is illustrated in Figure 1.16. It may be observed that the meridional rays shown appear to follow curved paths through the fiber core. Using the concepts of geometric optics, the gradual decrease in refractive index from the center of the core creates many refractions of the rays as they areeffectively incident on alarge number or high to low index interfaces. This mechanism is illustrated in Figure 1.17 where a ray is shown to be gradually curved, with an ever- increasing angle of incidence, until the conditions for total internal reflection are met, and the ray travels back towards the core axis, again being continuously refracted.

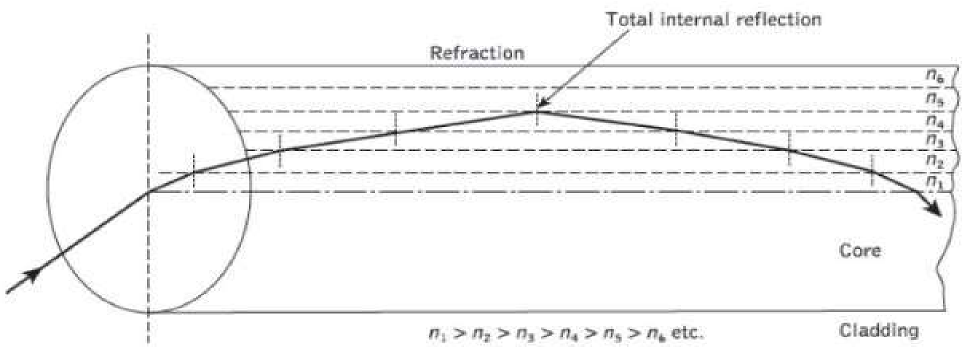


Figure 1.17 An expanded ray diagram showing refraction at the various high to low index interfaces within a graded index fiber, giving an overall curved ray path into the outer regions of the core.

Multimode graded index fibers exhibit far less intermodal dispersion than multimode step indexfibers due to their refractive index profile. Although many different modes are excited in the graded index fiber, the different group velocities of the modes tend to be normalized by the index grading. Again considering ray theory, the rays traveling close to the fiber axis have shorter paths when compared with rays which travel

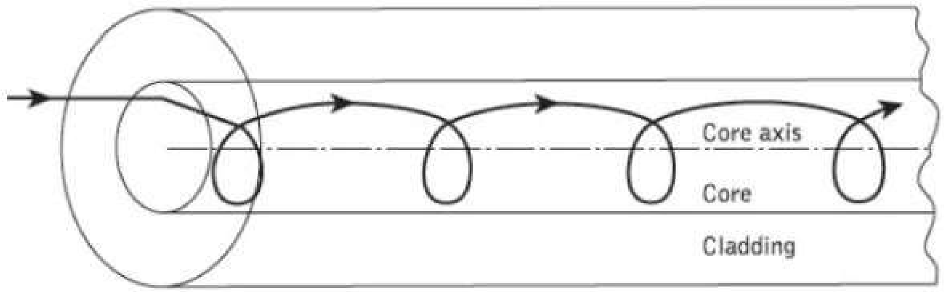


Figure 1.18 A helical skew ray path within a graded index fiber

However, the near axial rays are transmitted through a region of higher refractive index andtherefore travel with a lower velocity than the more extreme rays. This compensates for the shorter path lengths and reduces dispersion in the fiber. A similar situation exists for skew rays which follow longer helical paths, as illus- trated in Figure 1.18. These travel for the most part in the lower index region at greater speeds, thus giving the same mechanism of mode transit time equalization. Hence, multi-mode graded index fibers with parabolic or near-parabolic index profile cores have trans- mission bandwidths which may be orders of magnitude greater than multimode step index fiber bandwidths. Consequently, although they are not capable of the bandwidths attain- able with single- modefibers, suchmultimodegradedindex fibers havethe advantageof large corediameters (greater than 30 μm) coupled with bandwidths suitable for long- distance communication. The parameters defined for step index fibers (i.e. *NA*, Δ, *V*) may be applied to graded index fibers and give a comparison between the two fiber types. However, it must be noted that for graded index fibers the situation is more complicated since the numerical aperture is a function of the radial distance from the fiber axis. Graded index fibers, therefore, accept less light than corresponding step index fibers with the same relative refractive index difference.

Single-mode fiber

Theadvantageofthepropagation ofasinglemodewithinanopticalfiberisthatthesignaldispersion caused by the delay differences between different modes in a multimode fiber may be avoided. Multimode step index fibers do not lend themselves to the propagation of a single mode due to the difficulties of maintaining single-mode operation within the fiber when mode conversion (i.e. coupling) to other guided modes takes place at both input mismatches and fiber imperfections.

Hence, for the transmission of a single mode the fiber must be designed to allow propagation of only one mode, while all other modes are attenuated by leakage or absorption. Following the preceding discussion of multimode fibers, this may be achieved through choice of a suitable normalized frequencyforthefiber. For single-mode operation, onlythefundamentalLP01 mode can exist. Hence thelimitofsingle-modeoperationdependsonthelowerlimitofguidedpropagationforthe LP11 mode.ThecutoffnormalizedfrequencyfortheLP11 modeinstepindexfibersoccursat V_c= 2.405. Thus single-modepropagation of the LP01modeinstep index fibersis possibleover the range:

$$0 \leq V < 2.405 \tag{1.51}$$

as there is no cutoff for the fundamental mode. It must be noted that there are in fact two modes withorthogonalpolarization overthisrange,andthetermsingle-modeappliestopropagationof light of a particular polarization. Also, it is apparent that the normalized frequency for the fiber may be adjusted to within the range given in Eq. (1.51) by reduction of the core radius.

1. Cutoff wavelength

Itmaybenotedthatsingle-modeoperationonlyoccursaboveatheoreticalcutoffwavelength $\lambda_c$givenby:

$$\lambda_c = \frac{2\pi a n_1}{V_c}(2\Delta)^{\frac{1}{2}} \tag{1.52}$$

where V_c is the cutoff normalized frequency. Hence λ_c is the wavelength above which a particular fiber becomes single-moded.

Dividing Eq. (1.52) by $V = \frac{2\pi}{\lambda} a n_1 (2\Delta)^{\frac{1}{2}}$

$$\frac{\lambda_c}{\lambda} = \frac{V}{V_c} \tag{1.53}$$

Thus for step index fiber where V_c = 2.405, the cutoff wavelength is given by:

$$\lambda_c = \frac{V\lambda}{2.405} \tag{1.54}$$

An effective cutoff wavelength has been defined by the ITU-T which is obtained from a 2 m length of fiber containing a single 14 cm radius loop. This definition was produced because the first higherorder LP11mode is strongly affected by fiber length and curvature near cutoff. Recommended cutoff wavelength values for primary coated fiber range from 1.1 to 1.28 μm for single-mode fiber designed for operation in the 1.3μm wavelength region in order to avoid modal noise and dispersion problems. Moreover, practical transmission systems are generally operated close to the effective cutoff wave-length inorder to enhance thefundamental modeconfinement,but sufficientlydistantfromcutoffso that no power is transmitted in the second-order LP11 mode.

2. Mode-fielddiameterandspot size

Manypropertiesofthefundamentalmodearedeterminedbytheradialextentofitselectromagnetic field including losses at launching and jointing, micro bend losses, waveguide dispersion and thewidth of the radiation pattern. Therefore, the MFD is an important parameter for characterizing single-mode fiber properties which takes into account the wavelength-dependent field penetration into the fiber cladding. In this context it is a better measure of the functional properties of single- mode fiber than the core diameter. For step index and graded (near parabolic profile) single-mode fibers operating near the cutoff wavelength λc, the field is well approximated by a Gaussian distribution. In this case the MFD is generally taken as the distance between the opposite 1/e = 0.37 field amplitude points and the power 1/e2 = 0.135 points in relation to the corresponding values on the fiber axis.

Another parameter which is directly related to the MFD of a single-mode fiber is the spot size (or mode-field radius) $\omega 0$. Hence MFD = $2\omega 0$, where $\omega 0$is the nominal half width of the input excitation.

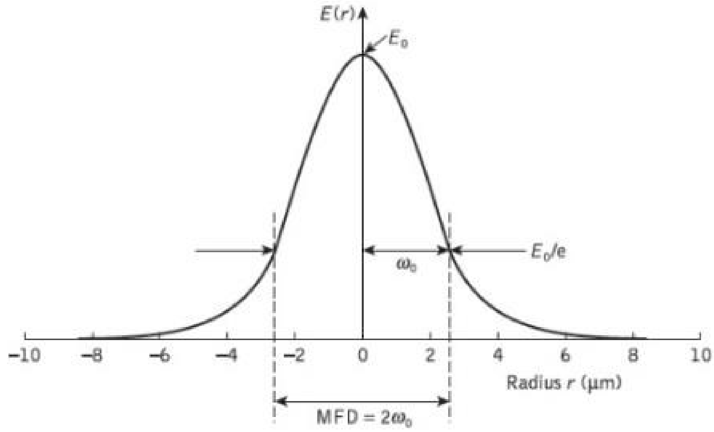


Figure 1.19 Field amplitude distribution $E(r)$ of the fundamental mode in a single-mode fiber illustrating the mode-field diameter (MFD) and spot size (ω_0)

The MFD can therefore be regarded as the single- mode analog of the fiber core diameter in multimode fibers. However, for many refractive index profiles and at typical operating wavelengths the MFD is slightly larger than the single-mode fiber core diameter.

Often, for real fibers and those with arbitrary refractive index profiles, the radial field distribution is not strictly Gaussian andhence alternativetechniques have been proposed. However,theproblemof defining the MFD and spot size for non-Gaussian field dis- tributions is a difficult one and at leasteight definitions exist.

3. Effectiverefractiveindex

The rate of change of phase of the fundamental LP01 mode propagating along a straight fiber is determinedbythephasepropagationconstant.ItisdirectlyrelatedtothewavelengthoftheLP01 modeλ01bythefactor2π,sinceβgivestheincreaseinphaseangleperunitlength.Hence:

$$\beta\lambda_{01} = 2\pi \quad \text{or} \quad \lambda_{01} = \frac{2\pi}{\beta} \tag{1.55}$$

Moreover, it is convenient to define an effective refractive index for single-mode fiber, sometimes referred to as a phase index or normalized phase change coefficient n_{eff}, by the ratio of the propagation constant of the fundamental mode to that of the vacuum propagation constant:

$$n_{eff} = \frac{\beta}{k} \tag{1.56}$$

Hence, the wavelength of the fundamental mode λ_{01} is smaller than the vacuum wave-length λ by the factor $1/n_{eff}$ where:

$$\lambda_{01} = \frac{\lambda}{n_{eff}} \tag{1.57}$$

It should be noted that the fundamental mode propagates in a medium with a refractive index $n(r)$ which is dependent on the distance *r*from the fiber axis. The effective refractive index cantherefore be considered as an average over the refractive index of this medium.

Within a normally clad fiber, not depressed-cladded fibers, at long wavelengths (i.e. small *V*values) the MFD is large compared to the core diameter and hence the electric field extends far into the cladding region. In this case the propagation constant β will be approximately equal to n_2k(i.e. the claddingwavenumber)andtheeffectiveindexwillbesimilartotherefractiveindexofthe cladding n_2. Physically, most of the power is transmitted in the cladding material.

At short wavelengths, however, the field is concentrated in the core region and the propagation constant β approximates to the maximum wave number n_1k. Following this discussion, and as indicated previously, then the propagation constant in single-mode fiber varies over the interval $n_2k < \beta < n_1k$. Hence, the effective refractive index will vary over the range $n_2 < n_{eff} < n_1$.

4. Groupdelayandmodedelay factor

Thetransittimeorgroupdelay$\tau_g$foralightpulsepropagatingalongaunitlengthoffiberisthe inverse of the group velocity υ_g. Hence:

$$\tau_g = \frac{1}{\upsilon_g} = \frac{d\beta}{d\omega} = \frac{1}{c}\frac{d\beta}{dk} \qquad (1.61)$$

The group index of a uniform plane wave propagating in a homogeneous medium has been determined as:

$$N_g = \frac{c}{\upsilon_g}$$

However, for a single-mode fiber, it is usual to define an effective group index* N_{ge} By:

$$N_{ge} = \frac{c}{\upsilon_g} \qquad (1.62)$$

Where $\upsilon_g$is considered to be the group velocity of the fundamental fiber mode. Hence, thespecific group delay of the fundamental fiber mode becomes:

$$\tau_g = \frac{N_{ge}}{c} \qquad (1.63)$$

Fibermaterials

Most of the fibers are made up of glass consisting of either Silica (SiO_2) or .Silicate. High- loss glass fibers are used for short-transmission distances and low-loss glass fibers are used for long distance applications. Plastic fibers are less used because of their higher attenuation than glass fibers. Glass Fibers.

The glass fibers are made from oxides. The most common oxide is silica whose refractive index is 1.458_at 850 nm. To get different indexfibers,the dopants such as GeO_2,P_2O_5 areadded to silica. $GeO_2$and P_2O_3increase the refractive index whereas fluorine or B_20_3decreasesthe refractive index.

Fewfibercompositionsaregivenbelowasfollows,

(i) GeO_2– SiO_2Core:SiO_2Cladding

(ii) P_2Q_5–SiO_2,Core;SiO_2Cladding

Theprinciplerawmaterialforsilicaissand.Theglasscomposedofpuresilicais referredto as silica glass, nitrous silica or fused silica. Some desirable properties of silica are,

(i) Resistancetodeformationattemperatureashighas1000°C.

(ii) Highresistancetobreakagefromthermalshock.

(iii) Goodchemical durability.

(iv) Hightransparencyinboththevisibleandinfraredregions.

BasicRequirementsandConsiderationsinFiberFabrication

(i) Opticalfibersshouldhavemaximumreproducibility.

(ii) Fibersshouldbefabricatedwithgoodstabletransmissioncharacteristicsi.e.,the fiber should have invariable transmission characteristics in long lengths.

(iii) Differentsize,refractiveindexandrefractiveindexprofile,operatingwavelengths material. Fiber must be available to meet different systemapplications.

(iv) Thefibersmustbeflexibletoconvertintopracticalcableswithoutanydegradation of their characteristics.

(v) Fibers must be fabricated in such a way that a joining (splicing) of the fiber should not affect its transmission characteristics and the fibers may be terminated or connected together with less practical difficulties.

FiberFabricationinaTwoStageProcess

(i) Initiallyglassisproducedandthenconvertedintoperformorrod.

Glassfiberisamixtureofselenides,sulfidesandmetaloxides.Itcanbeclassified into,

1. HalideGlassFibers
2. ActiveGlassFibers
3. ChalgenideGlassFibers.

Glass is made of pure SiO_2which refractive index 1.458 at 850 nm. The refractive index of SiO_2can be increased (or) decreased by adding various oxides are known as dopant. The oxides GeO2 or P2O3 increases the refractive index and B_2O_3decreases the refractive index of SiO_2 .

Thevariouscombinationsare,

(i) GeO_2SiO_2Core;SiO_2cladding

(ii) P_2O_3– SiO_2Core;SiO_2cladding

(iii) SiO_2Core;B_2O_3,-SiO_2cladding

(iv) GeO_2-B_2O_3-SiO_2,Core;B_2O_3-SiO_2cladding.

Fromabove,therefractiveindexofcoreismaximumcomparedtothecladding.

(1) HalideGlassFibers

A halide glass fiber contains fluorine, chlorine, bromine and iodine. The most common Halide glass fiber is heavy "metal fluoride glass". It uses ZrF_4as a major component.This fluoride glass is known by the name ZBLAN Since it is constituents are ZrF_4, BaF_2, LaF_3A1F_3, and NaF.

Thepercentagesoftheseelementstoform ZBLANfluorideglassisshownas follows,

Materials	Molecular percentage
ZrF_4	54%
BaF_2	20%
LaF_3	4.5%
$A1F_3$	3.5%
NaF	18%

Thesematerialsadd up tomakethecoreofaglassfiber.Byreplacing ZrF_4 by HaF_4,thelower refractive index glass is obtained.

Theintrinsiclossesoftheseglassesis0.01to0.001dB/km

(2) ActiveGlass Fibers

Active glass fibers are formed by adding erbium and neodymium to the glass fibers. The above material performs amplification and attenuation

(3) ChalgenideGlass Fibers

Chalgenide glass fibers are discovered in order to make use of the nonlinear properties of glass fibers. It contains either "S", "Se" or "Te", because they are highly nonlinear and it also contains one element from “Cl”, "Br”, “Cd”,”Ba” or”Si”.The mostly used chalgenide glass is AS_2-S_3, $AS_{40}S_{58}Se_2$is used to make the core and $AS_2S_3$is used to make the cladding material of the glass fiber. The insertion loss is around 1 dB/m.

PlasticOptical Fibers

Plastic optical fibers are the fibers which are made up of plastic material. The core of this fiberis madeupof Polymethylmethacrylate (PMMA) orPerflourmated Polymer (PFP).Plastic optical fibers offer more attenuation than glass fiber and is used for short distance applications.

These fibers are tough and durable due to the presence of plastic **material**. The modulus of this plastic material is two orders **of** magnitude lower than that of silica and even a 1 mm diameter graded index plastic optical fiber can be installed **in** conventional fiber cable routes. The diameter of the core of these fibers is 10-20 times larger than that of glass fiber which reduces the connector losses without sacrificing coupling efficiencies. So we can use inexpensive connectors, splices and transceivers made up of plastic injection-molding technology. Graded index plastic optical fiber is in great demand in customer premises to deliver high-speed services due to its high bandwidth.

UNIT-II

SIGNALDISTORTIONINOPTICALFIBERS

Introduction

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

Attenuation

- Attenuationisameasureofdecayof signalstrengthorlossoflightpowerthatoccurs as light pulses propagate through the length of the fiber.
- In optical fibers the attenuation is mainly caused by two physical factors absorption and scatteringlosses. Absorption isbecauseof fibermaterialandscatteringdue to structural imperfection within the fiber. Nearly 90 % of total attenuation is caused by Rayleigh scattering only. Microbending of optical fiber also contributes to the attenuation of signal.
- The rate at which light is absorbed is dependent on the wavelength of the light and the characteristics of particular glass. Glass is a silicon compound, by adding different additionalchemicalstothebasicsilicondioxidetheopticalpropertiesoftheglasscanbe changed.
- TheRayleighscatteringiswavelengthdependentandreducesrapidlyasthe wavelength of the incident radiation increases.

- The attenuation of fiber is governed by the materials from which it is fabricated, the manufacturing process and the refractive index profile chosen. Attenuation loss is measured in dB/km.

AttenuationUnits

Asattenuationleadsto alossofpoweralongthefiber,theoutputpowerissignificantlylessthan the couples power. Let the couples optical power isp(0) i.e.at origin (z =0).

Thenthepoweratdistancezisgivenby,

$$P(z) = P(0)e^{-\alpha_p z} \quad \text{...(2.1.1)}$$

where,$\alpha_p$isfiberattenuationconstant(perkm).

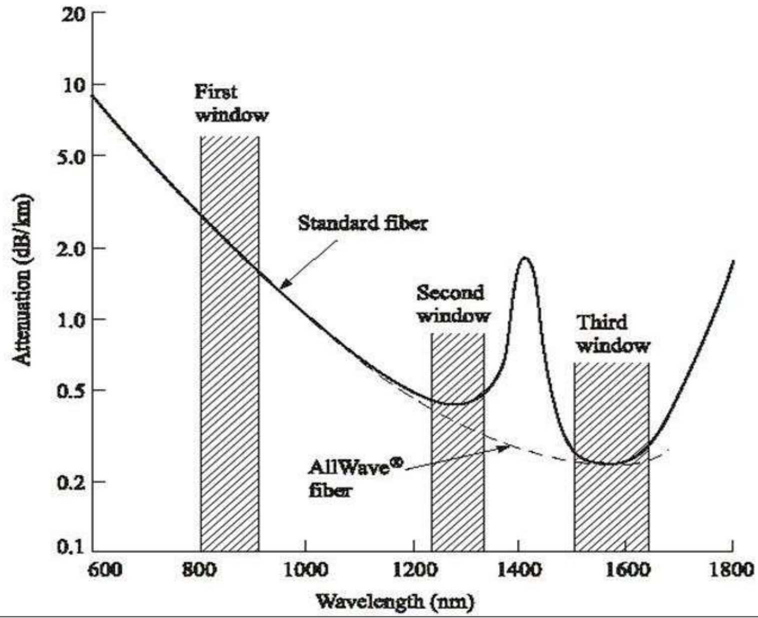
$$\alpha_p = \frac{1}{z} \ln\left[\frac{P(0)}{P(z)}\right]$$

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

$$\alpha_{dB/km} = 4.343 \ \alpha_p \ \text{per km}$$

Thisparameterisknownasfiberlossorfiber attenuation.

- Attenuation isalsoafunctionofwavelength.Opticalfiberwavelengthasafunction of wavelength is shown in Fig. 2.1.1.



Optical fiber attenuation as a function of wavelength yields nominal values of 0.5 dB/km at 1310 nm and 0.3 dB/km at 1550 nm for standard single mode fiber. Absorption by the water molecules causes the attenuation peak around 1400nm for standard fiber. The dashed curve is the attenuation for low water peak fiber. Irfan khan

Fig2.1.1:Opticalfiberwavelengthasafunctionofwavelength

Example2.1.1:Alowlossfiberhasaveragelossof3dB/kmat900nm.Computethelength over which –

a)Powerdecreasesby50% b)Powerdecreasesby75%.

Solution : α=3dB/km

$$\Rightarrow \quad \frac{p(0)}{p(z)} = 50\ \% = 0.5$$

a) Powerdecreasesby50%.

 isgivenby,

$$\left[\frac{200\ \mu W}{P(z)}\right] = 10^{2.4}$$

$$3 = 10 \cdot \frac{1}{z} \log [0.5]$$

z= **1km…Ans.**

b) $\frac{P(0)}{P(z)} = 25\ \% = 0.25$ Since power decreaseby 75

%.

$$3 = 10 \text{ x } \frac{1}{z} \log[0.25]$$

z =**2km…Ans.**

Example2.1.2: Fora30kmlongfiberattenuation0.8dB/kmat1300nm.Ifa200µwattpower is launched into the fiber, find the output power.

Solution: z=30km

□= 0.8 dB/km

P(0)= 200

µW

Attenuationinopticalfiberisgivenby,

$$0.8 = 10 \text{ x } \frac{1}{30} \log \left[\frac{200\ \mu W}{P(z)}\right]$$

$$2.4 = 10 \text{ x } \log \left[\frac{200\ \mu W}{P(z)}\right]$$

Example2.1.3:Whenmeanopticalpowerlaunchedintoan8kmlengthoffiberis12μW,the mean optical power at the fiber output is 3 μW.

Determine–

OverallsignalattenuationindB.

Theoverallsignalattenuationfora10kmopticallinkusingthesamefiberwithsplicesat 1 km intervals, each giving an attenuation of 1 dB.

Solution: Given : z=8km

P(0)=120μW

P(z) = 3 μW

1) Overallattenuationisgivenby,

$$\alpha = 10\ .\log\left[\frac{P(0)}{P(z)}\right]$$

$$\alpha = 10\ .\log\left[\frac{120}{3}\right]$$

$$\alpha = 16.02\ \text{dB}$$

2) Overallattenuationfor10km,

Attenuation per km

$\propto_{dB} = \frac{16.02}{z} = \frac{16.02}{8} = 2.00\ \text{dB/km}$ Attenuationin10 kmlink= 2.00 x10 =20dB

In10kmlinktherewillbe9splicesat1kminterval.Eachspliceintroducingattenuation of 1 dB.

Totalattenuation= 20dB+ 9dB= **29dB**

Example2.1.4:Acontinuous12kmlongopticalfiberlinkhasalossof1.5dB/km.

- Whatistheminimumopticalpowerlevelthatmustbelaunchedintothefiberto maintain as optical power level of 0.3 μW at the receiving end?
- Whatistherequiredinputpowerifthefiberhasalossof2.5 dB/km?

Solution:Given data :z= 12km

=1.5dB/km P(0)

= 0.3 μW

- Attenuationinopticalfiberisgivenby,

$$\alpha = 10 \text{ x } \frac{1}{z} \log\left(\frac{P(0)}{P(z)}\right)$$

$$1.5 = 10 \text{ x } \frac{1}{12} \log\left(\frac{0.3\ \mu W}{P(z)}\right)$$

$$\log\left(\frac{0.3\ \mu W}{P(z)}\right) = \frac{1.5}{0.833}$$

=1.80

$$\left(\frac{0.3\ \mu W}{P(z)}\right) = 10^{1.8}$$

$$P(z) = \left(\frac{0.3\ \mu W}{10^{1.8}}\right) = \frac{0.3}{63.0}$$

$$P(z) = 4.76 \times 10^{-9} W$$

Opticalpoweroutput=**$4.76x10^{-9}$W** **… Ans.**

ii) Inputpower= P(0)

When α=2.5dB/km

$$\alpha = 10 \times \frac{1}{z} \log\left(\frac{P(0)}{P(z)}\right)$$

$$2.5 = 10 \times \frac{1}{z} \log\left(\frac{P(0)}{4.76 \times 10^{-9}}\right)$$

$$\log\left(\frac{P(0)}{4.76 \times 10^{-9}}\right) = \frac{2.5}{0.833} = 3$$

$$\frac{P(0)}{4.76 \times 10^{-9}} = 10^3 = 1000$$

P(0)=4.76µW

Inputpower=**4.76 µW** **…Ans.**

Example 2.1.5 : Optical power launched intofiber attransmitter end is150 µW. The power at the end of 10 km length of the linkworking infirstwindows is– 38.2 dBm.Another system of same length working in second window is 47.5 µW. Same length system working in third window has 50 % launched power. Calculate fiber attenuation for each case and mention wavelength of operation. **[Jan./Feb.-2009,4Marks]**

Solution:Given data:

P(0)=150 µW

z= 10km

$$P(z) = -38.2 \text{ dBm} \Rightarrow \begin{cases} -38.2 = 10 \log \dfrac{P(z)}{1 \text{ mW}} \\ P(z) = 0.151 \ \mu W \end{cases}$$

z=10km

$$\boxed{\alpha = 10 \text{ x } \frac{1}{z} \log \left[\frac{P(0)}{P(z)}\right]}$$

Attenuationin1stwindow:

$$\propto_1 = 10 \text{ x } \frac{1}{10} \log \left[\frac{150}{0.151}\right]$$

$$\propto_1 = \mathbf{2.99\ dB/km}$$

Attenuationin2ndwindow:

$$\propto_2 = 10 \ \text{x} \ \frac{1}{10} \log \left[\frac{150}{47.5}\right]$$

$$\propto_2 = \mathbf{0.49\ dB/km}$$

Attenuationin3rdwindow:

$$\propto_3 = 10 \ \text{x} \ \frac{1}{10} \log \left[\frac{150}{75}\right]$$

$$\propto_3 = \mathbf{0.30\ dB/km}$$

Wavelength in 1st window is 850 nm.

Wavelengthin2ndwindowis1300nm.

Wavelengthin3rdwindowis1550nm.

Example2.1.6:Theinputpowertoanopticalfiberis2mWwhilethe powermeasuredat the output end is 2 µW. If the fiber attenuation is 0.5 dB/km, calculate the length of the fiber.

Solution: Given:P(0)=2mwatt=2x10^{-3}watt

P(z)=2µwatt=2x10^{-6}watt

α=0.5dB/km

$$\alpha = 10 \text{ x } \frac{1}{z}\left[\frac{P(0)}{P(z)}\right]$$

$$z = 60 \text{ km}$$ **...Ans.**

$$0.5 = 10 \text{ x } \frac{1}{z}\log\left[\frac{2 \text{ x } 10^{-3}}{2 \text{ x } 10^{-6}}\right]$$

$$0.5 = \frac{1}{z} \text{x} 3$$

$$z = \frac{3}{0.05}$$

Absorption

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

Absorptioninopticalfiberiscausedbythesethree mechanisms.

1. Absorptionbyatomicdefectsintheglasscomposition
2. Extrinsicabsorptionbyimpurityatomsintheglassmaterial
3. Intrinsicabsorptionbythebasicconstituentatomsofthefibermaterial.

AbsorptionbyAtomicDefects

Atomic defects are imperfections in the atomic structure of the fiber materials such as missing molecules,highdensityclustersofatomgroups.Theseabsorptionlossesarenegligiblecompared with intrinsic and extrinsic losses.

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

1rad(Si)=0.01 J.kg

ThehighertheradiationintensitymoretheattenuationasshowninFig 2.2.1.

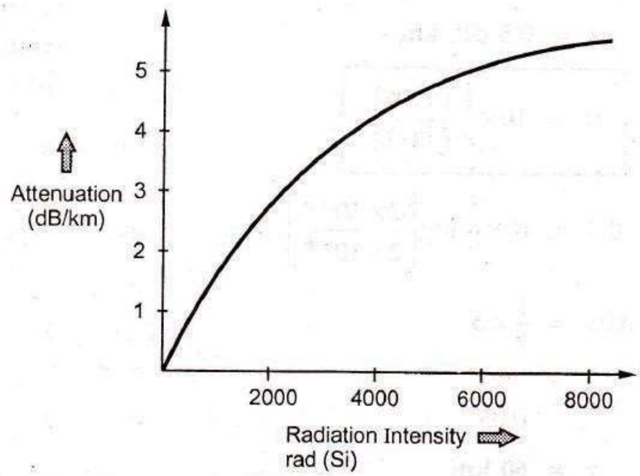


Fig. 2.2.1 Ionizing radiation intensity Vs fiber attenuation

ExtrinsicAbsorption

Extrinsic absorption occurs due to electronic transitions between the energy level and because of chargetransitionsfromoneiontoanother.Amajorsourceofattenuationisfromtransitionofmetal impurity ions such as iron, chromium, cobalt and copper. These losses can be upto 1 to 10 dB/km. Theeffectofmetallicimpuritiescanbereducedbyglassrefining techniques.

- Anothermajorextrinsiclossiscausedbyabsorptiondueto **OH(Hydroxil)**ionsimpurities dissolved in glass. Vibrations occur at wavelengths between 2.7 and 4.2 µm.

  Theabsorptionpeaksoccursat1400,950and750nm.Thesearefirst,secondandthird overtones respectively.

- Fig.2.2.2showsabsorptionspectrumforOHgroup insilica.Betweenthese absorption peaks there are regions of low attenuation.

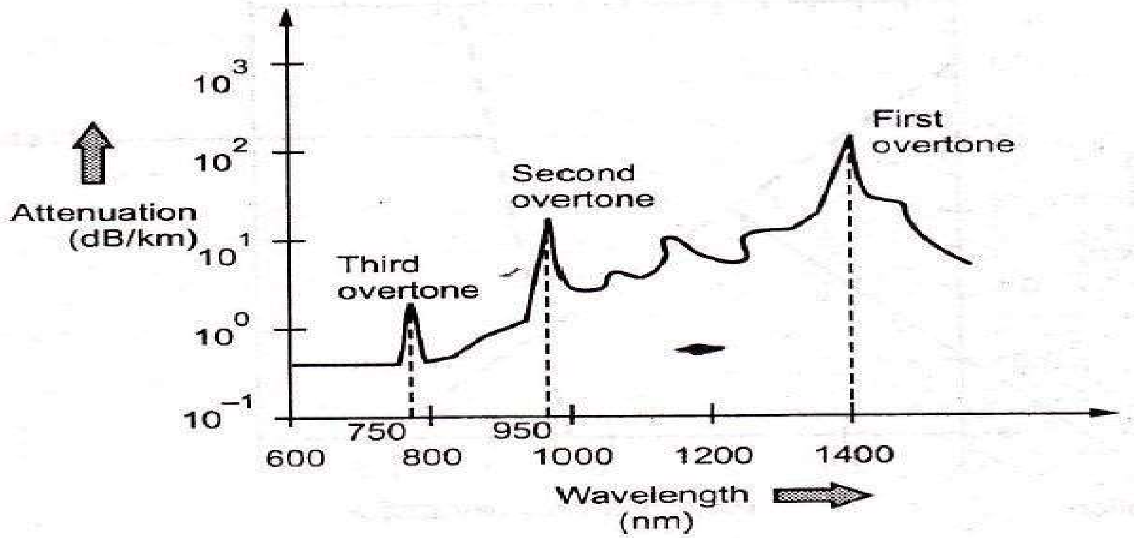


Fig. 2.2.2 Absorption spectra for OH group

IntrinsicAbsorption

Intrinsic absorption occurs when material is in absolutely pure state, no density variation and inhomogenities.Thusintrinsicabsorptionsetsthefundamentallower limitonabsorptionforany particular material.

- Intrinsicabsorptionresultsfromelectronicabsorptionbands inUVregionand from atomic vibration bands in the near infraredregion.
- The electronic absorption bands are associated with the band gaps of amorphous glass materials. Absorption occurs when a photon interacts with an electron in the valene band and excites it to a higher energy level. UV absorption decays exponentially with increasing wavelength (λ).

- In the IR (infrared) region above 1.2 µm the optical waveguide loss is determined by presence of the OH ions and inherent IR absorption of the constituent materials. The inherent IR absorption is due to interaction between the vibrating band and the electromagnetic field of optical signal this results in transfer of energy from field to the band, thereby giving rise to absorption, this absorption isstrong becauseof many bonds present in the fiber.

Theultravioletlossatanywavelengthisexpressedas,

$$\alpha_{uv} = \frac{154.2}{46.6\,x + 60} \times 10^{-2} \times e^{\left(\frac{4.63}{\lambda}\right)} \quad \text{... (2.2.1)}$$

where,xismolefractionofGeO_2. λ is

operating wavelength. α_{uv}

is in dB/km.

 Thelossininfrared(IR)region(above1.2µm)isgivenbyexpression:

$$\alpha_{IR} = 7.81 \times 10^{11} \times e^{\left(\frac{-48.48}{\lambda}\right)} \quad \text{...(2.2.2)}$$

TheexpressionisderivedforGeO_2-SiO_2glassfiber.

RayleighScattering Losses

Scattering losses exists in optical fibers because of microscopic variations in the material density and composition. As glass is composed by randomly connected network of molecules and several oxides (e.g. SiO_2, $GeO_2$and P_2O_5), these are the major cause of compositional structure fluctuation. These two effects results to variation in refractive index and Rayleigh type scattering of light.

Rayleighscatteringoflightisduetosmalllocalizedchangesintherefractiveindexofthe core and cladding material.

Therearetwocausesduringthemanufacturingof fiber.

1. Thefirstisduetoslightfluctuationinmixingofingredients.Therandomchanges because of this are impossible to eliminate completely.

2. The other cause isslight change indensity as the silica cools and solidifies. When light ray strikes such zones it gets scattered in all directions. The amount of scatter depends on the size of the discontinuity compared with the wavelength of the light so the shortest wavelength (highest frequency) suffers most scattering.

Fig. 2.3.1showsgraphicallytherelationshipbetweenwavelengthandRayleighscattering loss.

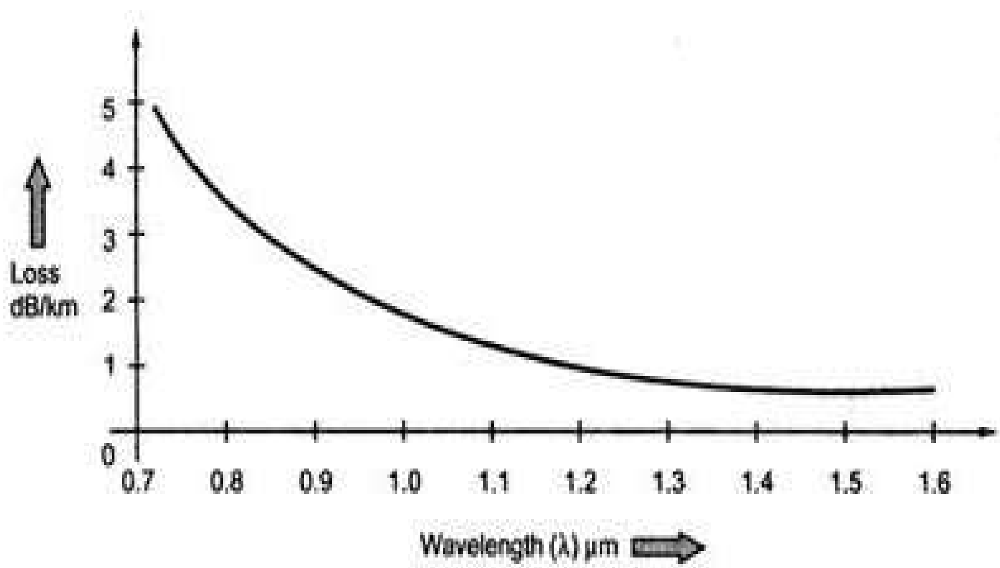


Fig. 1 Scattering loss

Scatteringlossforsinglecomponentglassisgivenby,

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

where,n= Refractiveindex

k_B=Boltzmann'sconstant

β_T=Isothermalcompressibilityof material

T_f=Temperatureatwhichdensityfluctuationsarefrozenintotheglassasit solidifies (fictive temperature)

Anotherformofequationis

$$\propto_{scat} = \frac{8\pi^8}{3\lambda^4} n^8 p^2 k_B T_f \beta_T \text{ neper} \propto_{scat} = \frac{8\pi^3}{3\lambda^4} (\delta_n^2)^2 \delta v$$

... (2.3.2)

where, P=Photoelasticcoefficient

where, δ_n^2= Mean square refractive indexfluctuation

δv =Volumeoffiber

- Multimode fibers have higher dopant concentrations and greater compositional fluctuations.Theoveralllossesinthisfibersaremoreascomparedtosinglemode fibers.

MieScattering:

- Linearscatteringalsooccurs atinhomogenitiesandthesearisefromimperfections inthe fiber's geometry, irregularities in the refractive index and the presence of bubbles etc. caused during manufacture. Careful control of manufacturing process can reduce Mie scattering to insignificant levels.

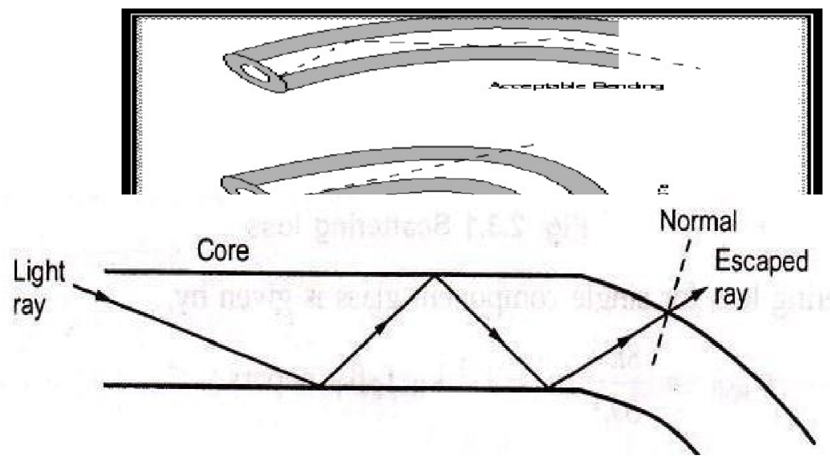
BendingLoss

Radiative losses occur whenever an optical fiber undergoes a bend of finite radius of curvature.Fiberscanbesubjectedtotwotypesofbends:a)Macroscopicbends(havingradii that are large as compared with the fiber diameter)

b)Randommicroscopicbendsoffiberaxis

Lossesduetocurvatureandlossescausedbyanabruptchangeinradius ofcurvaturearereferredto as'bendinglosses.'

- Thesharpbendofafibercausessignificantradiativelossesandthereisalso possibility of mechanical failure. This is shown in Fig. 2.4.1.



Asthecorebendsthenormalwillfollow itandtheraywillnowfinditselfonthewrongsideofcritical angle and will escape. The sharp bends are therefore avoided.

Theradiationlossfromabentfiberdependson –Fieldstrengthofcertaincriticaldistancex$_c$ from fiber axis where power is lost through radiation.

TheradiusofcurvatureR.

Thehigherordermodesare lesstightlyboundto thefibercore,thehigherordermodes radiate out of fiber firstly.

Formultimodefiber,theeffectivenumberofmodesthatcanbeguidedbycurvedfiberis where,αisgradedindexprofile.

□is core–claddingindexdifference. n_2 is refractive index of cladding.k is wave propagation constant $\left(\frac{2\pi}{\lambda}\right)$.

N∞istotalnumberofmodesinastraight fiber.

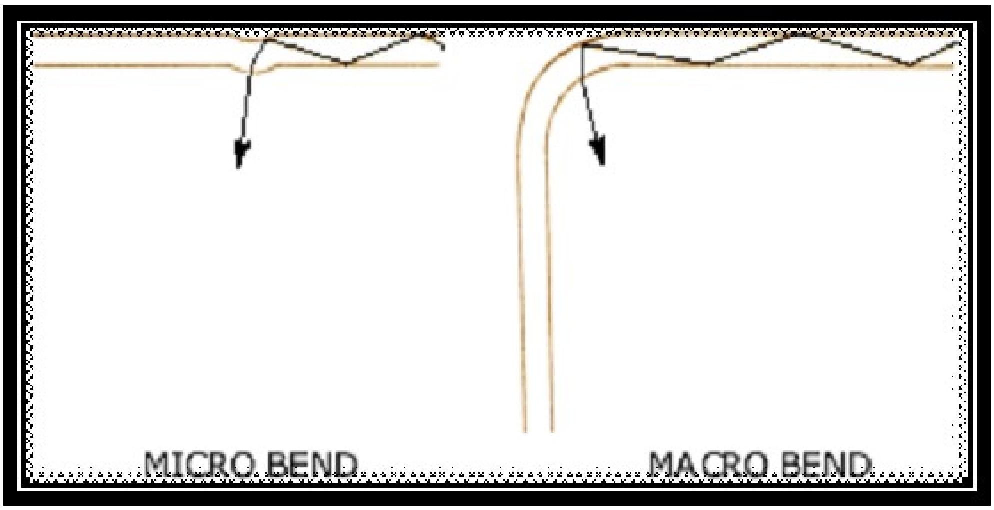
$$N_\infty = \frac{\alpha}{\alpha+2}(n_1\ k\ a)^2\Delta \qquad \text{...(2.4.2)}$$

Microbending

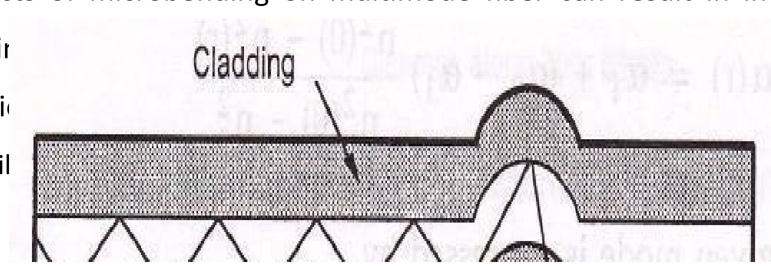
MicrobendingLoss

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

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



- Microbending isalossduetosmallbendingordistortions.Thissmallmicrobending is not visible. The losses due to this are temperature related, tensile related or crush related.
- The effects of microbending on multimode fiber can result in increasing attenuation (dependi



ghs on the spectral attenuati llation and testing. Fig.2.4.2 il

Macrobending

For slight bends, the loss is extremely small and is not observed.As the radius of curvature decreases, the loss increases exponentially until at a certain critical radius of curvature loss becomes observable. If the bend radius is made a bit smaller once this threshold point has been reached, the losses suddenly become extremely large. It is known that any bound core mode has an evanescent field tail in the cladding which decays exponentially as a function of distance from the core. Since this field tail moves along with the field in the core, part of the energy of a propagating mode travels in the fiber cladding. When a fiber is bent, the field tail on the far side of the centre of curvature must move faster to keep up with the field in the core, for the lowest order fiber mode. At a certain critical distance x_c, from the centre of the fiber; thefieldtail would have to move faster than the speed of light to keep up withthe core field. Since this is not possible the optical energy in the field tail beyond $x_c$radiates away.
The amount of optical radiation from a bent fiber depends on the field strength at x_c and on the radius of curvature R. Since higher order modes are bound less tightly to the fiber core than lower order modes, the higher order modes will radiate out of the fiber first.

- The change in spectral attenuation caused by macrobending is different to microbending. Usually there are no peaks and troughs because in a macrobending no light is coupled back into the core from the cladding as can happen in the case of microbends.

- The macrobending losses are cause by large scale bending of fiber. The losses are eliminated when the bends are straightened. The losses can be minimizedby not exceeding the long term bend radii. Fig. 2.4.3 illustrates macrobending.

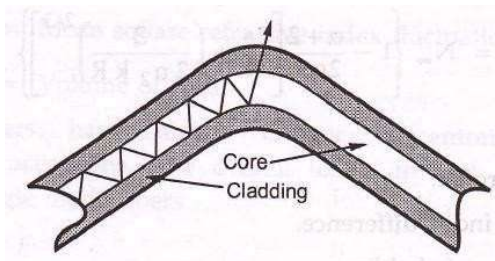
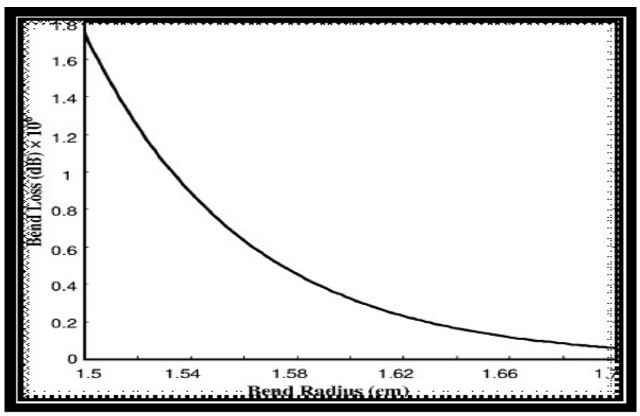


Fig. 2.4.3 Macrobending



Macro bending Loss

CoreandCladdingLoss

- Sincethecoreandcladdinghavedifferentindicesofrefractionhencethey have different attenuation coefficients α_1 and α_2 respectively.

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

- Forstepindexfiber,thelossforamodeorder(v,m)isgivenby,

$$\propto_{v\,m} = \propto_1 \frac{P_{core}}{P} + \propto_2 \frac{P_{cladding}}{P}$$ ... (2.5.1)

Forlow-ordermodes,theexpressionreduced to

$$\propto_{v\,m} = \propto_1 + (\propto_2 + \propto_1)\frac{P_{cladding}}{P}$$ ... (2.5.2)

where, $\frac{P_{core}}{P}$ and $\frac{P_{cladding}}{P}$ arefractionalpowers.

- Forgradedindexfiber,lossatradialdistanceisexpressedas,

... (2.5.3)

Thelossforagivenmodeisexpressedby,

$$\propto_{Graded\ Index} = \frac{\int_0^\infty \propto(r)\,P(r)\,r\,dr}{\int_0^\infty P(r)\,r\,dr}$$ ... (2.5.4)

where,P(r)ispowerdensityofthatmodelatradialdistancer.

SignalDistortioninOpticalWaveguide

- The pulse gets distorted as it travels along the fiber lengths. Pulse spreading in fiber is referred as dispersion. Dispersion is caused by difference in the propagation times of light rays that takes different paths during thepropagation. The lightpulses travelling down the fiber encounter dispersion effect because of this the pulse spreads out in time domain. Dispersion limitsthe information bandwidth. The distortion effects can be analyzed by studying the group velocities in guided modes.

InformationCapacityDetermination

- DispersionandattenuationofpulsetravellingalongthefiberisshowninFig.2.6.1.

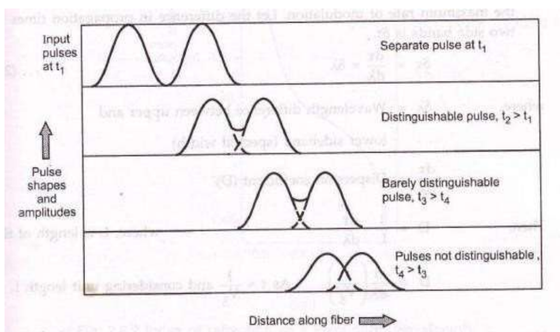


Fig. 2.6.1 Dispersion and attenuation in fiber

- Fig. 2.6.1 shows, after travelling some distance, pulse starts broadening and overlap with the neighbouring pulses. At certain distance the pulses are noteven 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.

GroupDelay

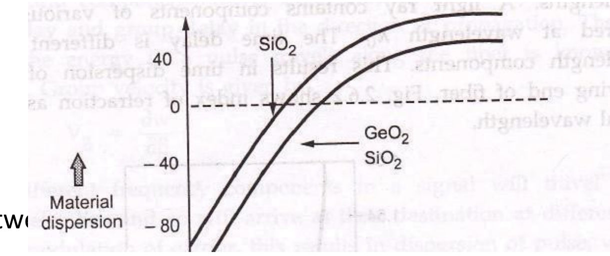
- Consider a fiber cable carrying optical signal equally with various modes and each mode contains all the spectral components inthe wavelength band.All the spectral components travel independently and they observe different **timedelay** and **group delay** inthe direction of propagation. The velocity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

$$V_g = \frac{\partial w}{\partial \beta} \qquad \text{...(2.6.1)}$$

- 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$\delta\tau$.

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

(2.6.2)



where, $\delta\tau$ =Wavelengthdifferencebetw

(spectralwidth) $\frac{d\tau}{d\lambda}$ Dispersion coefficient (D)

Then, $D = \frac{1}{L}.\frac{d\tau}{d\lambda}$ here,Lislengthoffiber.

$$D = \frac{d}{d\lambda}\left(\frac{1}{V_g}\right)$$ As $\tau = \frac{1}{V_g}$ onsideringunitlengthL= 1.

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

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

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

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

- Dispersionismeasuredinpicosecondspernanometerperkilometer.

MaterialDispersion

Materialdispersion isalsocalledaschromaticdispersion.Materialdispersion existsdueto change in index of refraction for different wavelengths. A light raycontains components of various wavelengths centered at wavelength λ_{10}. The time delay is different for different wavelength components. This results in time dispersion of pulse at the receiving end of fiber. Fig. 2.6.2 shows index of refraction as a function of optical wavelength.

Thematerialdispersionforunitlength(L=1)isgivenby

$$D_{mat} = \frac{-\lambda}{c} x \frac{d^2n}{d\lambda^2}$$

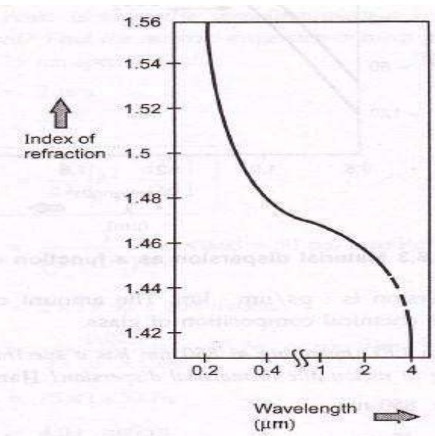


Fig. 2.6.2 Index of refraction as a function of wavelength

… (2.6.4)

where, c=Lightvelocity

λ=Centerwavelength

$\frac{d^2n}{d\lambda^2}$= Second derivativeof index ofrefraction w.r.twavelength

Negativesignshowsthattheuppersidebandsignal(lowestwavelength)arrives before the lower sideband (highest wavelength).

- Theunitofdispersionis:ps/nm.km.Theamountofmaterialdispersion depends upon the chemical composition of glass.

Example2.6.1:AnLEDoperatingat850nmhasaspectralwidthof45 nm.Whatisthe pulse spreading in ns/km due to material dispersion?

Solution:Given: λ=850nm

σ =45nm

pulsebroadeningduetomaterialdispersionisgivenby,

$\sigma_m = \sigma$ LM

Consideringlength L= 1metre

$$\text{Material dispersion constant } D_{mat} = \frac{-\lambda}{c} \cdot \frac{d^2n}{d\lambda^2}$$

ForLEDsourceoperatingat850nm, $\left|\lambda^2 \frac{d^2n}{d\lambda^2}\right|$=0.025

$$M = \frac{1}{c\lambda}\left|\lambda^2 \frac{d^2n}{d\lambda^2}\right| = \frac{1}{(3 \times 10^5)(850)} \times 0.025$$

M=9.8ps/nm/km

σ_m=**441ns/km** …

Ans.

WaveguideDispersion

- Waveguide dispersion is caused by the difference in the index of refraction betweenthecoreand cladding,resulting ina‘drag’ effectbetweenthe core and cladding portions of the power.
- Waveguide dispersion is significant only in fibers carrying fewer than 5-10 modes. Since multimode optical fibers carry hundreds of modes, they will not have observable waveguide dispersion.
- Thegroupdelay(τ_{wg})arisingduetowaveguidedispersion.

$$\left(\tau_{wg}\right) = \frac{L}{c}\left[n_2 + n_2 \Delta \frac{d\,(kb)}{dk}\right]$$ …

(2.6.5)

Where, b=Normalizedpropagation constant k = 2π / λ (group velocity)

NormalizedfrequencyV,

$$V = ka(n_1^2 - n_2^2)^{\frac{1}{2}}$$

$$\tau_{wg} = \frac{L}{c}\left[n_2 + n_2 \Delta \frac{d\,(V_b)}{dV}\right]$$

Thesecondterm $\frac{d(V_b)}{dV}$ iswaveguidedispersionandismodedependentterm..

- As frequency isafunction ofwavelength,thegroup velocity of theenergyvaries with frequency. The produces additional losses (waveguide dispersion). The propagation constant (b) varies with wavelength, the causes of which are independent of material dispersion.

ChromaticDispersion

- The combination of material dispersion and waveguide dispersion is called chromatic dispersion. These losses primarily concern the spectral width of transmitter and choice of correct wavelength.

* Agraphofeffectiverefractive indexagainst wavelength illustratesthe effectsof material, chromatic and waveguide dispersion.

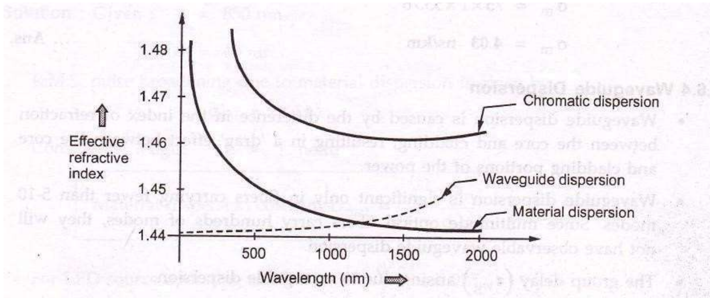


Fig. 2.6.4 Graph of effective refractive index against wavelength showing effects of chromatic, waveguide and material dispersion

Materialdispersionandwaveguidedispersioneffectsvary invaryinoppositesensesasthe wavelength increased,but at an optimumwavelength around 1300 nm, two effects almost cancel each other and chromatic dispersion isat minimum. Attenuation istherefore alsoat minimum and makes 1300 nm a highly attractive operating wavelength.

ModalDispersion

As only a certain number of modes can propagate down the fiber, each of these modes carries the modulation signal and each one is incident on the boundary at a different angle, they will each have their own individual propagation times. The net effect is spreading of pulse, this form o dispersion is called modal dispersion.

* Modaldispersiontakesplaceinmultimodefibers.Itismoderatelypresent

ingradedindexfibersandalmosteliminated insinglemodestepindex fibers.

- Modaldispersion isgivenby,

$$\Delta t_{modal} = \frac{n_1 Z}{c}\left(\frac{\Delta}{1-\Delta}\right)$$

where Δt_{modal}=Dispersion

n_1 = Core refractiveindex

Z = Total fiber length

c=Velocityoflightinair

□= Fractionalrefractiveindex $\left(\frac{n_1 - n_2}{n_1}\right)$

Puttinginaboveequation $\Delta = \frac{(NA^2)Z}{2n_1 c}$

$$\Delta t_{modal} = \frac{(NA^2)Z}{2n_1\ c}$$

$$t_{r\ mod} = 0.44\ (\Delta t_{modal})\pi r^2$$

Example2.6.3:Fora singlemodefibern2=1.48and=0.2%operatingatA=1320 nm,

compute the waveguide dispersion if $V.\frac{d^2(Vb)}{dv^2} = 0.26.$

Solution: n2=1.48

0.2

=1320nm

Waveguidedispersionisgivenby,z

$$D_{wg}(\lambda) = \frac{-n_2\Delta}{c}\left[V\frac{d^2(Vb)}{dV^2}\right]$$
$$= \frac{-1.48 \times 0.2}{3 \times 10^5 \times 1320}[0.20]$$

-1.943picosec/nm.

km.

HigherOrder Dispersion

S.

$$S = \frac{dD}{d\lambda}$$

Higherorderdispersiveeffectiveeffectsaregovernedbydispersionslope

where, D is total dispersion

Also,

$$S = \left(\frac{2\pi c}{\lambda^2}\right)^2 \beta_3 + \left(\frac{4\pi c}{\lambda^3}\right) \beta_2$$ where,

$\beta_2$and$\beta_3$aresecondandthirdorderdispersionparameters.

- DispersionslopeSplaysanimportantroleindesigningWDMsystem

DispersionInducedLimitations

- Theextentofpulse broadeningdependsonthewidth andthe shape ofinput pulses. The pulse broadening is studied with the help of wave equation.

BasicPropagationEquation

- Thebasicpropagationequationwhichgovernspulseevolution inasingle mode fiber is given by,

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i\beta_2}{2} \cdot \frac{\partial^2 A}{\partial t^2} - \frac{\beta_3}{6} \frac{\partial^3 A}{\partial t^3} = 0$$

where,

β_1,$\beta_2$and$\beta_3$aredifferentdispersionparameters.

ChirpedGaussianPulses

- Apulseissaidtobechirpedifitscarrierfrequencychangeswithtime.
- ForaGaussianspectrumhavingspectralwidthσ_ω,thepulsebroadening factor is given by,

$$\frac{\sigma^2}{\sigma_0^2} = \left(1 + \frac{C\beta_2 L}{2\sigma_2^2}\right)^2 + (1 + V_\omega^2)\left(\frac{\beta_2 L}{2\sigma_0^2}\right)^2 + (1 + C + V_\omega^2)^2 \left(\frac{\beta_3 L}{4\sqrt{2\sigma_0^3}}\right)\pi r^2$$

where, $V_\omega = 2\sigma_\omega\sigma_0$

LimitationsofBitRate

- Thelimitingbitrateisgivenby,

$$4B\,\sigma \leq 1$$

- Theconditionrelatingbitrate-distanceproduct(BL)anddispersion(D)isgiven

$$BL\ |S|\sigma_\lambda^2 \leq \frac{1}{\sqrt{8}}$$

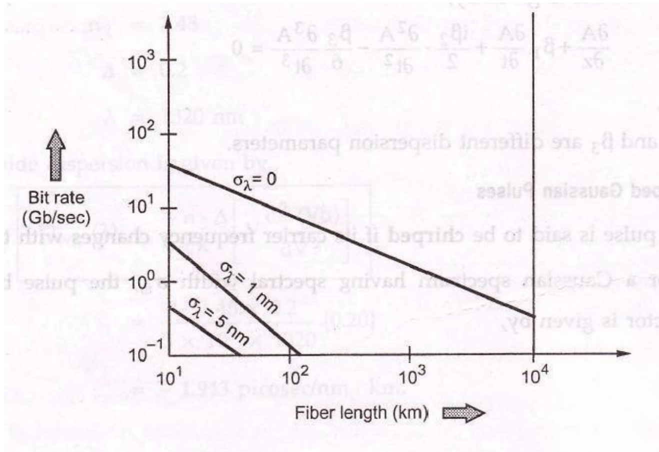


Fig. 2.6.5 Dependence of bit rate on fiber length

where,Sisdispersionslope.Limitingbitrateasinglemodefibersasafunctionoffiberlength for $\sigma\lambda$ = 0, a and 5nm is shown in fig. 2.6.5.

PolarizationModeDispersion(PMD)

- Differentfrequencycomponentof apulseacquiresdifferentpolarizationstate(such as linear polarization and circular polarization). This results in pulse broadening is kno**w as polarization mode dispersion (PMD).**
- PMDisthelimitingfactorforopticalcommunicationsystemathighdata rates. The effects of PMD must be compensated.

PulseBroadeninginGI Fibers

- The core refractive index varies radially in case of graded index fibers, hence it supports multimode propagation with a low intermodal delay distortion and high data rate over long distance is possible. The higher order modes travelling in outer regions of the core, willtravel faster than the lower order modes travelling in high refractive index region. If the index profile is carefully controlled, then the transit times of theindividual modes will be identical, so eliminating modal dispersion.

  - Ther.m.spulsebroadeningisgivenas:

$$\sigma = \left(\sigma^2_{\text{intermodal}} + \sigma^2_{\text{intermodal}}\right)^{1/2} \qquad \text{... (2.7.1)}$$

where,

$\sigma_{intermodal}$–R.M.Spulsewidthduetointermodaldelaydistortion.

$\sigma_{intermodal}$–R.M.Spulsewidthresultingfrompulsebroadeningwithineach mode.

- Theintermodaldelayandpulsebroadeningarerelatedbyexpressiongiven byPersonick.

$$\sigma_{\text{intermodal}} = \left(\langle \tau_g^2 \rangle - \langle \tau_g \rangle^2\right)^{1/2} \qquad \text{...(2.7.2)}$$

Where$\tau_g$isgroupdelay.

Fromthistheexpressionforintermodalpulsebroadeningisgivenas:

$$\propto_{\text{intermodal}} = \frac{\mathrm{LN_1}\Delta}{2\mathrm{c}} \cdot \frac{\propto}{\propto + 1} \left(\frac{\propto + 2}{3 \propto + 2} \right)^{1/2} \mathrm{x}$$

$$\left[c_1^2 + \frac{4c_1 c_2(\propto + 1)}{2\propto + 1} + \frac{16\Delta^2 c_2^2 (\propto + 1)^2}{(5\propto + 2)(3\propto + 2)} \right]^{1/2}$$

...(2.7.3)

$$c_1 = \frac{\propto - 2 - E}{\propto + 2} \ and\ c_2 = \frac{3 \propto - 2 - 2c}{2(\propto + 2)}$$

- Theintramodalpulsebroadeningisgivenas :

$$\sigma_{intramodal}^2 = \left(\frac{\sigma\lambda}{\lambda}\right)^2 \left\langle \left(\lambda \frac{d\tau g}{d\lambda}\right)^2 \right\rangle \quad ...(2.7.4)$$

Whereσλisspectralwidthofoptical source.

Solvingtheexpression
gives :

$$\sigma_{intramodal}^2 = \frac{L}{c} \cdot \frac{\sigma\lambda}{\lambda} \left[\left(-\lambda^2 \frac{d^2 n_1}{d\lambda^2} \right)^2 - N_1 c_1 \Delta \right.$$

$$\left(2\lambda^2 \frac{d^2 n_1}{d\lambda^2}\cdot\frac{\alpha}{\alpha+1} - N_1 c_1 \Delta \frac{4\alpha^2}{(\alpha+2)(3\alpha+2)}\right)\Big]^{1/2}$$

ModeCoupling

Aftercertaininitiallength,thepulsedistortionincreaseslessrapidlybecauseofmodecoupling. The energy from one mode is coupled to other modes because of Structural imperfections, Fiber diameter variations, Refractive index variations, Microbends in cable.Due to the mode coupling, average propagation delay become less and intermodal distortion reduces.Suppose certain initial coupling length = L_C, mode coupling length, over L_C = Z. Additional loss associated with mode coupling = h (dB/ km).Therefore the excess attenuation resulting from mode coupling = hZ.The improvement in pulse spreading by mode coupling is given as :

$$hZ\left(\frac{\sigma_c}{\sigma_0}\right) = C$$

where, C is constant independent of all dimensional quantities and refractive indices.$\sigma_c$is pulse broadeningunder mode coupling.$\sigma_0$is pulse broadening in absence of mode coupling. For long fiber length's the effect of mode coupling on pulse distortion is significant. For a graded index fiber, the effect of distance on pulse broading

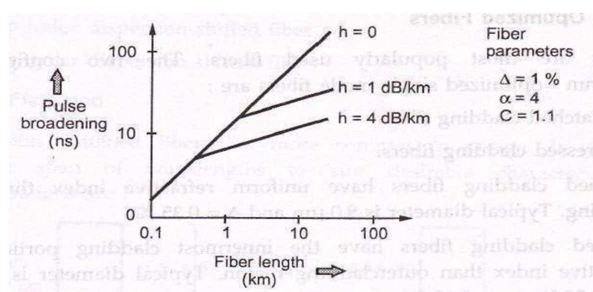


Fig. 2.8.1 Mode coupling effects on pulse broadening

forvarious coupling losses are shown

Design Optimization

Featuresofsinglemodefibersare: Longer life,Lowattenuation,SignalTransferqualityisgood, Modal noise is absent,Largest BW-distance product.

Basicdesign –optimizationincludesthefollowing: Dispersion,Modefield,Diameter,bendingloss, Refractive index profile,Cut-off wavelength.

RefractiveIndexProfile

Dispersion of single mode silica fiber is lowest at 1300 nm while its attenuation isminimum at 1550 nm. For archiving maximum transmission distance the dispersion null should be at the wavelength of minimum attenuation. The waveguide dispersion is easier to control than the material dispersion. Therefore a variety of core-claddingrefractive.

1300nm–Optimized Fibers

Thesearemostpopularlyusedfibers.Thetwoconfigurationsof1300nm –optimizedsingle mode fibers are

- Matchedcladdingfibers.
- Dressedcladdingfibers.

Matchedcladdingfibershaveuniformrefractiveindexthroughoutitscladding.Typical diameteris9.0µmandΔ= 0.35%.

Dressedcladdingfibershavetheinnermostcladdingportionhaslowrefractiveindexthan outrcladdingregion.Typical diameteris8.4µmandΔ_1 =0.25 %,Δ_2 =0.12%.

Fig2.9.1showsbothtypesof fibers.

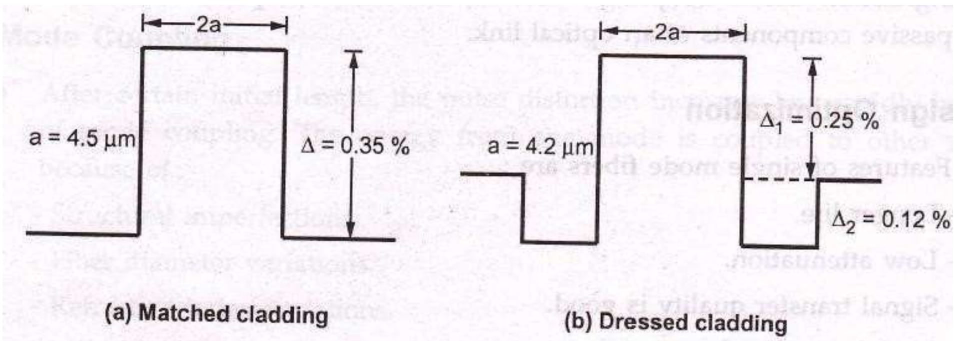


Fig. 2.9.1 1300 nm - optimized refractive index profile

DispersionShiftedFibers

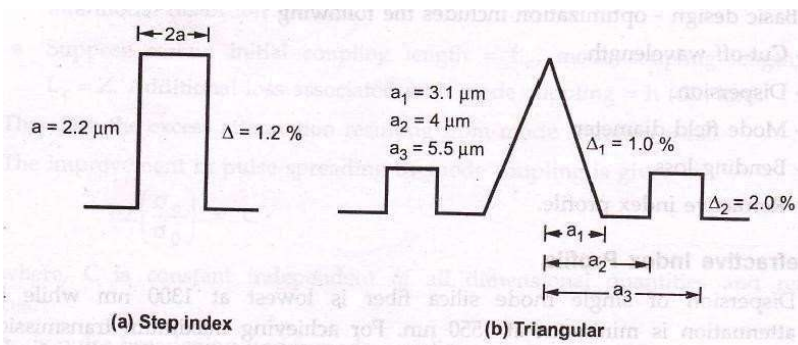


Fig. 2.9.2 Dispersion shifted fibers

2. Theadditionofwavelengthandmaterialdispersioncan shiftthezero dispersion point of longer wavelength. Two configurations of dispersion shifted fibers are

DispersionFlattened

Dispersionflattenedfibersaremorecomplextodesign.Itoffersmuchbroaderspanof wavelengths to suit desirable characteristics. Two configurations are :

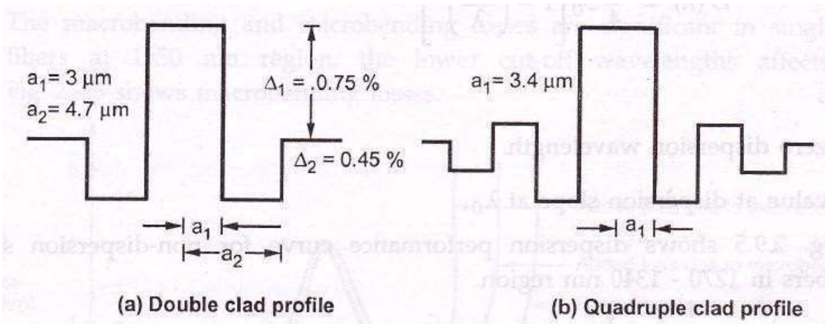


Fig. 2.9.3 Dispersion flattened

- Fig2.9.4showstotalresultantdispersion.

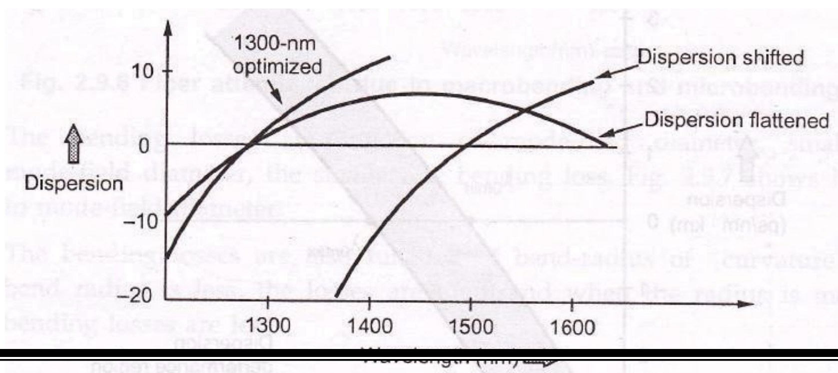


Fig. 2.9.4 Total resultant dispersion

DispersionCalculations

Thetotaldispersionconsistsofmaterialandwaveguidedispersions.Theresultant intermodal dispersion is given as,

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

where,τisgroupdelayperunitlengthof fiber.

Thebroadeningσofanopticalpulseisgiven

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

where,$\sigma_\lambda$ishalfpowerspectralwidthof source.

Asthedispersionvarieswithwavelengthandfibertype.Differentformulaeareused to calculate dispersions for variety of fiber at different wavelength. For a non –

$$D(\lambda) = \frac{\lambda}{4} S_0 \left[1 - \left(\frac{\lambda_0}{\lambda} \right)^4 \right]$$

dispersionshiftedfiberbetween1270nm to 1340nmwavelength,theexpressionfor dispersion is given as :

where,$\lambda_0$iszerodispersionwavelength.

S_0 is value at dispersion slop at λ_0.

Fig2.9.5showsdispersionperformancecurvefornon-dispersionshiftedfibers in 1270 – 1340 nm region.

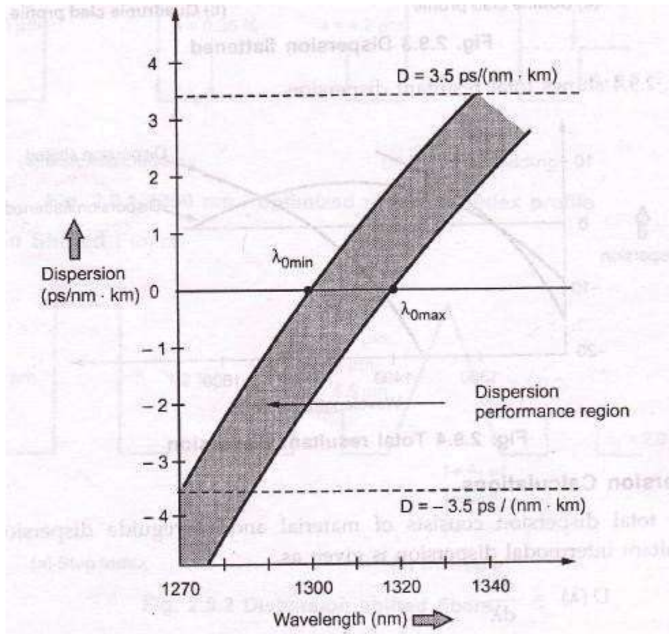


Fig. 2.9.5

Maximumdispersionspecifiedas3.5ps/(nm.km)markedasdottedlineinFig.2.9.5.

Thecut-offfrequencyofanoptical fiber

The cut-off frequency of an optical fiber is determined not only by the fiber itself (modaldispersionincaseof multimodefibersandwaveguidedispersion incaseof single mode fibers) but also by the amount of material dispersion caused by the spectral width of transmitter.

BendingLossLimitations

Themacrobendingandmicrobendinglossesaresignificant insinglemodefibersat1550nm region, the lower cut-off wavelengths affects more. Fig. 2.9.6 shows macrobending losses.

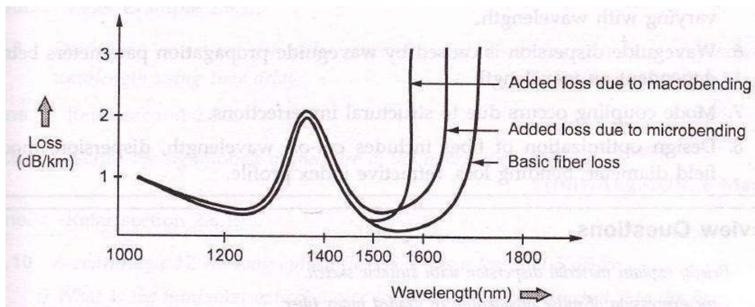


Fig. 2.9.6 Fiber attenuation due to macrobending and microbending

The bending losses are function of mode-filed diameter, smaller the mode-field diameter, the smaller the bending loss. Fig. 2.9.7 shows loss due to mode-field diameter.Thebending losses are also function of bend-radius of curvature. If the bend radius is less, the losses are more and when the radius is more, the bending losses are less.

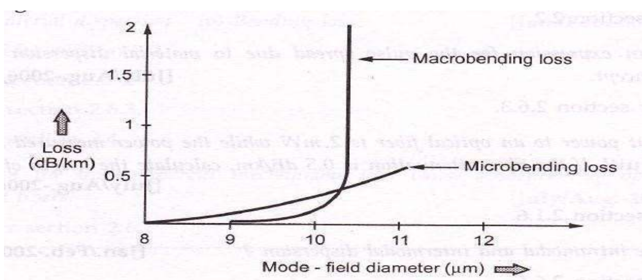


Fig. 2.9.7 Loss due to mode field diameter variation

Opticalfiberconnectors

An optical fiber connector terminates the end of an optical fiber, and enables quicker connection and disconnection than splicing. The connectors mechanically couple and alignthecoresoffiberssolight canpass. Betterconnectorsloseverylittlelightduetoreflectionor misalignment of the fibers. In all, about 100 different types of fiber optic connectors have been introduced to the market.

An optical fiber connector is a flexible device that connects fiber cables requiring a quick connection and disconnection. Optical fibers terminate fiber-optic connections to fiber equipmentorjointwofiber connectionswithoutsplicing. Hundredsof optical fiberconnector types are available, but the key differentiator is defined by the mechanical coupling techniques and dimensions. Optical fiber connectors ensure stable connections, as they ensure the fiber endsare optically smooth and the end-to-end positions are properlyaligned.

An optical fiber connector is also known as a fiber optic connector. 1980s. Most fiber connectors are spring loaded.

The main components of an optical fiber connector are a ferrule, sub-assembly body, cable, stress relief boot and connector housing. The ferrule is mostly made of hardened materiallike stainless steel and tungsten carbide, and it ensures the alignment during connector mating. The connector body holds the ferrule and the coupling device serves the purpose of male-female configuration

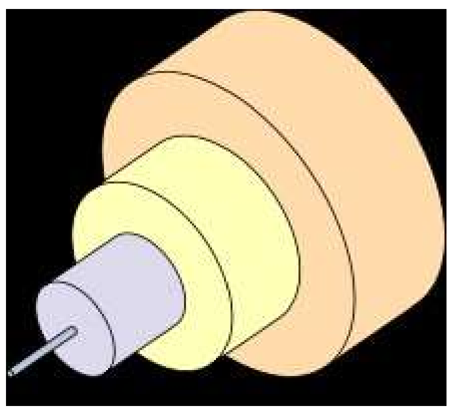
The fiber types for fiber optic connectors are categorized into simplex, duplex and multiple fiber connectors. A simplex connector has one fiber terminated in the connector, whereas duplex has two fibersterminated in the connector. Multiple fiber connectors can have two or more fibers terminated in the connector. Optical fiber connectors are dissimilar to other electronic connectors in that they do not have a jack and plug design. Instead they make use of the fiber mating sleeve for connection purposes.

Commonopticalfiberconnectorsincludebiconic,D4,ESCON,FC,FDDI,LCandSC.

- Biconicconnectorsuseprecisiontaperedendstohavelowinsertionloss.
- D4connectorshave akeyedbodyforeasy intermateability.
- ESCONconnectorsarecommonlyusedtoconnect fromawalloutlettoadevice.

- FCconnector(fixedconnectionconnector)isusedforsingle-modefibersandhigh- speed communication links.
- FDDIconnectorisaduplexconnectorwhichmakesuseofafixed shroud.
- LC connector (local connection connector) has the benefit of small-form-factor optical transmitter/receiver assemblies and is largely used in private and public networks.
- SC connector (subscriber connector) is used in simplex and multiple applications andis best suited for high-density applications.

In fiber-optic communication, asingle-mode optical fiber (SMF) is anoptical fiberdesigned to carry only a singlemodeof light - thetransverse mode. Modes are the possible solutions of theHelmholtz equation for waves, which is obtained by combining Maxwell's equationsand the boundary conditions. These modes define the way the wave travels through space, i.e. how the wave is distributed in space. Waves can have the same mode but have different frequencies. This is the case in single-mode fibers, where we can have waves with different frequencies, but of the same mode, which means that they are distributed in space in the same way, and that gives us a single ray of light. Although the ray travels parallel to thelength of the fiber, it is often called transverse modesince its electromagneticoscillations occurperpendicular(transverse)tothelengthofthefiber.The2009 NobelPrizein Physics was awarded to Charles K. Kaofor his theoretical work on the single-mode optical fiber.[1] The standard G.652 defines the most widely used form of single-mode optical fiber.[2]



Thestructureofatypicalsingle-modefiber.

1. Core 8-9 µm diameter
2. Cladding125µmdia.
3. Buffer250µmdia.
4. Jacket900µmdia.

Likemulti-mode optical fibers, single-mode fibers do exhibit modal dispersion resulting from multiple spatial modes but with narrower modal dispersion.[*citationneeded*] Single-mode fibers are therefore better at retaining the fidelity of each light pulse over longer distances than multi-mode fibers. For these reasons, single-mode fibers can have a higher bandwidththan multi-mode fibers. Equipment for single-mode fiber is more expensive than equipment for multi-mode optical fiber, but the single-mode fiber itself is usually cheaper in bulk.

Cross section of a single-mode optical fiber patch cord end, taken with a Fiberscope. The round circleisthe cladding, 125 micronsindiameter.Debris isvisibleasastreak onthe cross-section, and glows due to the illumination.

A typical single-mode optical fiber has a core diameter between 8 and 10.5 µm[6] and a cladding diameter of 125 µm. There are a number of special types of single-mode opticalfiberwhichhavebeenchemicallyorphysicallyalteredtogivespecialproperties,such asdispersion-shiftedfiber andnonzerodispersion-shiftedfiber.Dataratesarelimitedbypolarization mode dispersion and chromatic dispersion. As of 2005, data rates of up to 10 gigabits per second were possible at distances of over 80 km (50 mi) with commercially available transceivers (Xenpak). By using optical amplifiersand dispersion-compensating devices, state-of-the-artDWDMoptical systems can span thousands of kilometers at 10 Gbit/s, and several hundred kilometers at 40 Gbit/s.[*citationneeded*]

Thelowest-orderboundsmodeisascertainedforthewavelengthofinterestby solving Maxwell's equations for the boundary conditions imposed by the fiber, which are determined by the corediameter and the refractive indices of the core and cladding. The solution of Maxwell's equations for the lowest order bound mode will permit a pair of orthogonally polarized fields in the fiber, and this is the usual case in a communication fiber.

In step-index guides, single-mode operation occurs when the normalized frequency, *V*, is less thanorequalto2.405.For power-lawprofiles,single-modeoperationoccursfora normalized frequency, *V*, less than approximately where *g* is the profile parameter.

,

Cross section of a single-mode optical fiber patch cord end, taken with a Fiberscope. Theround circleisthe cladding, 125 micronsindiameter.Debris isvisibleasa streak onthe cross-section, and glows due to the illumination.

In practice, the orthogonal polarizations may not be associated with degenerate modes.OS1 and OS2 arestandard single-mode opticalfiberused withwavelengths1310 nmand 1550nm (size 9/125 µm) with a maximum attenuation of 1 dB/km (OS1) and 0.4dB/km (OS2). OS1 is defined in ISO/IEC 11801,[7] and OS2 is defined in ISO/IEC 24702.

Opticalfiber connectors

Optical fiber connectors are used to join optical fibers where a connect/disconnect capability is required. The basic connector unit is a connector assembly. A connector assembly consists ofanadapterandtwoconnectorplugs.Duetothesophisticatedpolishingandtuning procedures that may be incorporated into optical connector manufacturing, connectors are generally assembled onto optical fiber in a supplier's manufacturing facility. However, the assembly and polishing operations involved can be performed in the field, for example to make cross-connect jumpers to size.

Opticalfiberconnectorsareusedintelephonecompanycentraloffices,atinstallationson customer premises, and in outside plant applications. Their uses include:

- Makingtheconnectionbetweenequipmentandthetelephoneplantinthecentral office
- Connectingfiberstoremoteandoutsideplantelectronicssuchas OpticalNetwork Units (ONUs) and Digital Loop Carrier (DLC) systems
- Opticalcrossconnectsinthecentraloffice
- Patchingpanelsintheoutsideplanttoprovidearchitecturalflexibilityandto interconnect fibers belonging to different service providers
- Connectingcouplers,splitters,andWavelengthDivisionMultiplexers(WDMs)tooptical fibers
- Connectingopticaltestequipment tofibersfortestingandmaintenance.

Outside plant applications may involve locating connectors underground in subsurface enclosures that may be subject to flooding, on outdoor walls, or on utility poles. The closures that enclose them may be hermetic, or may be "free-breathing." Hermetic closures willprevent the connectors within beingsubjected to temperature swingsunless they are breached. Free-breathing enclosures will subject them to temperature and humidity swings, and possibly to condensation and biological action from airborne bacteria, insects, etc. Connectors in the underground plant may be subjected to groundwater immersion if the closures containing them are breached or improperly assembled.

The latest industry requirements for optical fiber connectors are inTelcordiaGR-326,*Generic Requirements for Singlemode Optical Connectors and Jumper Assemblies*.A*multi-fiber*optical connector is designed to simultaneously join multiple optical fibers together, with eachoptical fiber being joined to only one other optical fiber.The last part of the definition is included so as not to confuse multi-fiber connectors with a branching component, such as a coupler.Thelatterjoinsoneopticalfibertotwoormoreotheropticalfibers.Multi-fiber optical connectors are designed to be used wherever quick and/or repetitive connects and disconnects of a group of fibers are needed. Applications include telecommunications companies'CentralOffices(COs),installationsoncustomerpremises,andOutsidePlant(OSP) applications.Themulti-fiberopticalconnectorcanbeusedinthecreationofa low-costswitch for use in fiber optical testing. Another application is in cables delivered to a user with pre-terminated multi-fiber jumpers. This would reduce the need for field splicing, which could greatly reduce the number of hours necessary for placing an optical fiber cable in a telecommunications network. This, in turn, would result in savings for the installer of such cable.

The return loss RL is a measure of the portion of light that is reflected back to the source at the junction. It isexpressed in decibel. The higher the RL value in decibels, the lower are the reflections. Typical RL values lie between 35 and 50 dB for PC, 60 to 90 dB for APC and 20 to 40 dB for multimode fibres.

In the early days of fibre-optic plug-in connectors, the abutting endfaces were polished to an angle of 90° tothe fibre axis, while current standards require PC (Physical Contact) polishing or APC (Angled Physical Contact) polishing. The term HRL (High Return Loss) is frequently used, but it has the same meaning as APC.

In PC polishing, the ferrule is polished to a convex end to ensure that the fibre cores touch at their highest point. This reduces the occurrence of reflections at the junction.A further improvement in return loss is achieved by using the APC polishing technique. Here, the convex end surfaces of the ferrules are polished to an angle (8°) relative to the fibre axis. SC connectors are also sold with a 9° angle. They possess IL and RL values identical to 8°versions, and for this reason they have not established themselves worldwide.

ReturnLoss

In optics(particularly infiberoptics) a loss that takes place at discontinuities of refractive index, especially at an air-glassinterface such as a fiber endface. At those interfaces, afraction of the optical signalis reflected back toward the source. This reflection phenomenon is also called "**Fresnel reflection loss**," or simply "**Fresnel loss**."

Fiber optic transmission systems use lasersto transmit signals over optical fiber, and a high optical return loss (ORL) can cause the laser to stop transmitting correctly. The measurement ofORLisbecomingmoreimportantinthecharacterizationofopticalnetworksastheuse ofwavelength-division multiplexing increases. These systems use lasers that have a lower tolerance for ORL, and introduce elements into the network that are located in close proximity to the laser.

DefinitionofReturn Loss

In technical terms, RL is the ratio of the light reflected back from a device under test, P_{out}, to the light launched into that device, P_{in}, usually expressed as a negative number in dB.

$$RL=10\log_{10}(P_{out}/P_{in})$$

where isthereflectedpowerand istheincident,orinput,power.

Sources of loss include reflections and scattering along the fiber network. A typical RL value for anAngled Physical Contact (APC)connector is about -55dB,whiletheRL froman openflat polish to air istypically about -14dB. High RLis alarge concern in high bitrate digital or analog single mode systems and is also an indication of a potential failure point, or compromise, in any optical network.

UNIT III

OPTICALSOURCES

3.1Optical Sources

Opticaltransmittercovertselectricalinputsignalintocorrespondingopticalsignal. The optical signal is then launched into the fiber. Optical source is the major component in an optical transmitter .Popularly used optical transmitters are Light Emitting Diode (LED) and semiconductor

LaserDiodes(LD)

CharacteristicsofLightSourceofCommunication

Tobeusefulinanopticallink,alightsourceneedsthefollowing characteristics

Itmustbepossibletooperatethedevicecontinuouslyatavarietyoftemperaturesfor many years.

- It must be possible to modulate the light output over a wide range of modulating frequencies. For fiber links, the wavelength of the output should coincide with one of transmission windows for the fiber type used.
- To couple large amount of power into an optical fiber, the emitting area should be small.
- To reduce material dispersion in an optical fiber link, the output spectrum should be narrow.
- Thepowerrequirementforitsoperationmustbe low.
- Thelightsourcemustbecompatiblewiththemodernsolidstate devices.

- The optical output power must be directly modulated by varying the input current to the device.
- Betterlinearityofpreventharmonicsandintermodulationdistortion.
- Highcoupling efficiency.
- Highopticaloutput power.
- High reliability.
- Lowweightandlow cost.

Twotypesoflightsourcesusedinfiberopticsarelightemittingdiodes(LEDs)andlaser diodes (LDs).

LightEmittingDiodes(LEDs)

p-n Junction

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

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

Inanyopticalcommunicationsystemwhentherequirementsis1.Bitratef100-2—Mb/sec.

2.Opticalpowerintensof microwatts, LEDsarebest suitableoptical source.

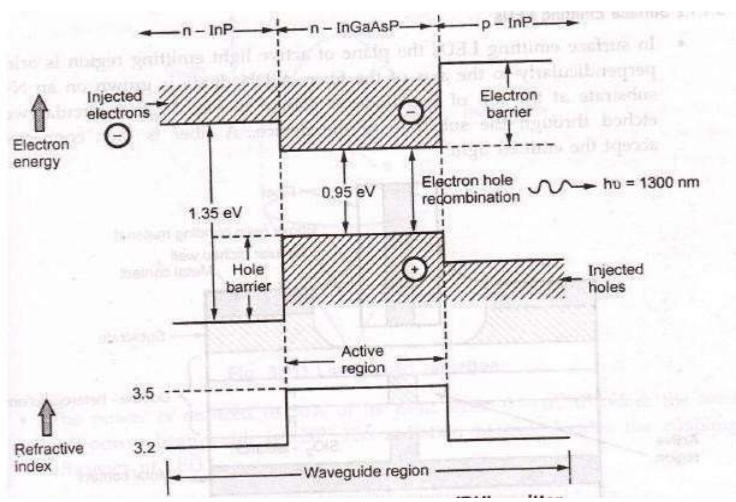
LED Structures

Heterojuncitons:

- A heterojunction is an interface between two adjoining single crystal semiconductors with different bandgap.
- Heterojuctionsareoftwotypes,Isotype(n-norp-p)orAntisotype(p-n).

DoubleHeterojunctions(DH):

In order to achieve efficient confinement of emitted radiation double heterojunctions are used in LED structure. A heterojunciton is a junction formed by dissimilar semiconductors.Double heterojunction (DH) is formed by two different semiconductors on each side of active region. Fig. 3.1.1 shows double heterojunction (DH) light emitter.



The crosshatched regions represent the energy levels of free charge. Recombination occurs only in active In GaAsP layer. The two materials have different band gap energies and different refractive indices. The changes in band gap energies create potential barrier forboth holes and electrons. The free charges can recombine only in narrow, well defined active layer side.

A double heterojunction (DH) structure will confine both hole and electrons to a narrow active layer. Under forward bias, there will be a large number of carriers injected into active region where they are efficiently confined. Carrier recombination occurs in smallactive region so leading to an efficient device. Another advantage DH structure is that the active region has a higher refractive index than the materials on either side, hence light emission occurs in an optical waveguide, which serves to narrow the output beam.

LEDconfigurations

AtpresentthearetwomaintypesofLEDusedin opticalfiberlinks Surface

emitting LED

EdgeemittingLED.

BothdevicesusedaDHstructuretoconstrainthecarriersandthelighttoanactivelayer.

SurfaceEmittingLEDs

In surface emitting LEDs the plane of active light emitting region is oriented perpendicularlyto the axis of the fiber. A DH diode is grown on an N-type substrate at the top of the diode as shown in Fig. 3.1.2. A circular well is etched through the substrate of the device. A fiber is then connected to accept the emitted

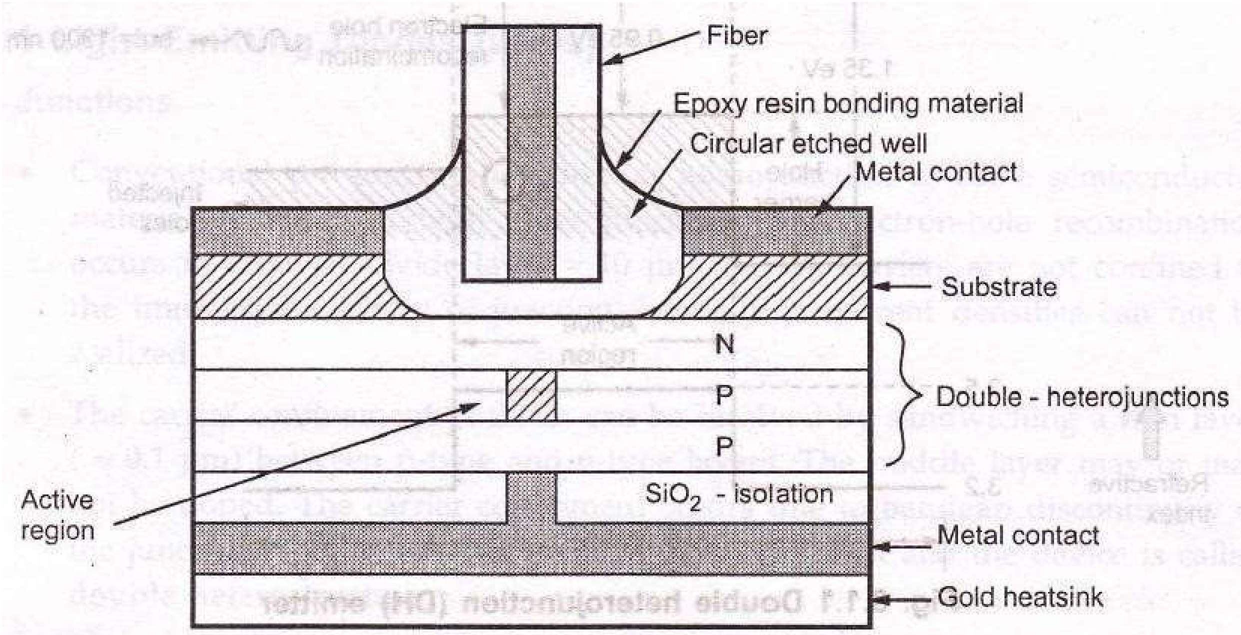


Fig. 3.1.2 Cross-section through a typical surface emitting LED

Atthebackofdeviceisagoldheatsink.Thecurrentflows throughthep-typematerial and forms the small circular active region resulting in the intense beam of light.

Diameter of circular active area = 50 µm

Thickness of circular active area = 2.5 µm

Currentdensity=2000A/cm2half-power

Emissionpattern=Isotropic,120obeamwidth.

The isotropic emission pattern from surface emitting LED is of Lambartian pattern. In Lambartianpattern,theemitting surface isuniformly bright,butitsprojected areadiminishes as cos θ, where $\theta$is the angle between the viewing direction andthenormal tothe surface as shown in Fig. 3.1.3. The beam intensity is maximum along the normal.

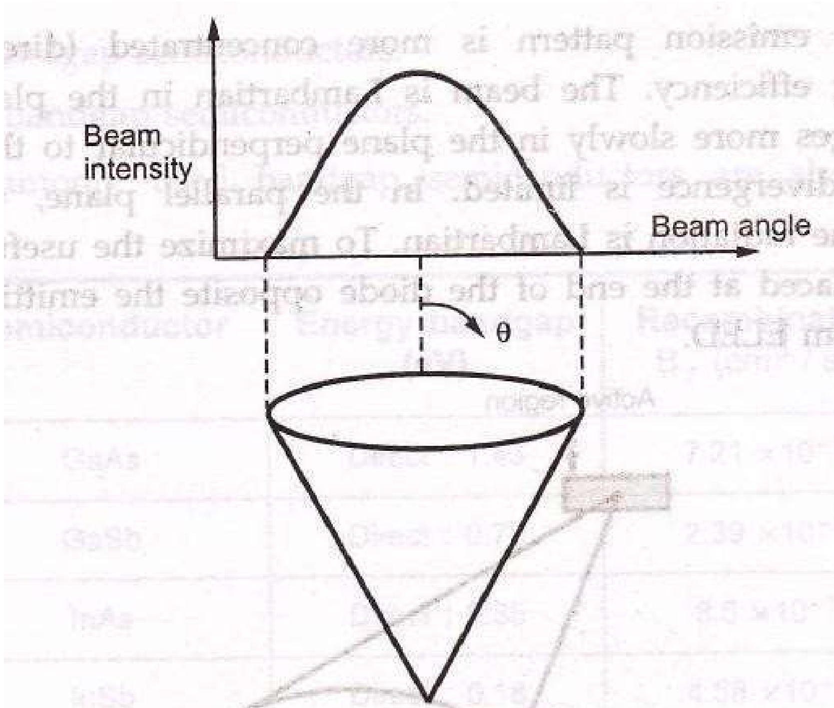


Fig. 3.1.3 Lambartian radiation

Thepower isreducedto50%ofitspeakwhen θ=60o,therefore thetotalhalf-power beamwidth is 120o. The radiation pattern decides the coupling efficiency of LED.

EdgeEmittingLEDS(ELEDs)

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

It consists of an active junction region which is the source of incoherent light and two guiding layers. The refractive index of guiding layers is lower than active region but higher than outer surrounding material. Thus a waveguide channel is form and optical radiation is directed into the fiber. Fig. 3.1.4 shows structure of LED

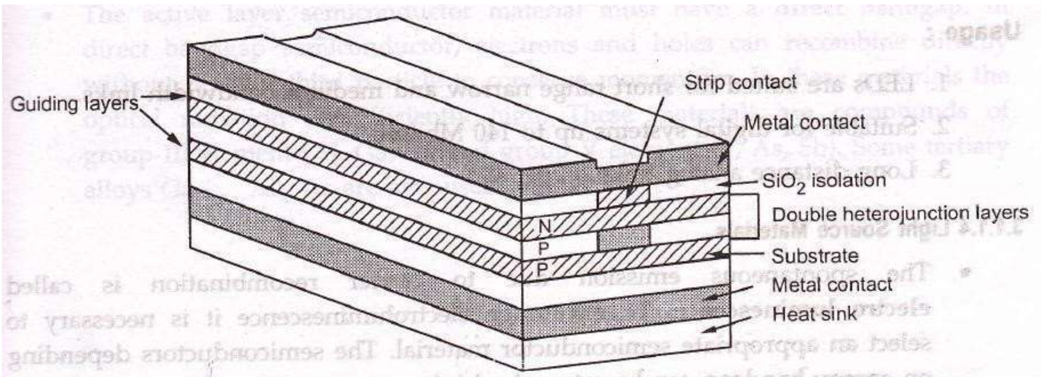


Fig. 3.1.4 Structure of edge emitting, DH, strip contact LED

Edge emitter's emission pattern is more concentrated (directional) providing improved coupling efficiency. The beam is Lambartian in the plane parallel to the junction but diverges more slowly in the plane perpendicular to the junction. In this plane, the beam divergence is limited. In the parallel plane, there is no beam confinement and the radiation is Lambartian. To maximize the useful output power, a reflector may be placed at the end of the diode opposite the emitting edge. Fig. 3.1.5 shows radiation from ELED.

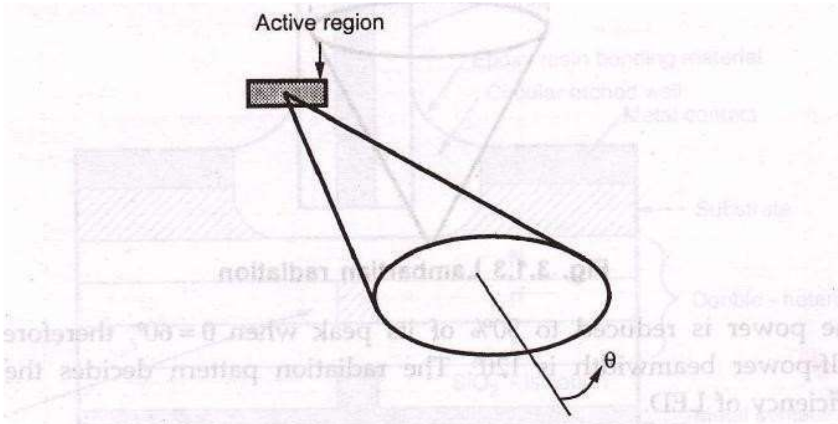


Fig. 3.1.5 Unsymmetric radiation from an edge emitting LED

FeaturesofELED:

- Linearrelationshipbetweenopticaloutputand current.
- Spectralwidth is25to400 nm for λ= 0.8–0.9μm.
- Modulationbandwidthismuchlarge.
- Notaffectedbycatastrophicgradationmechanismshencearemorereliable.
- ELEDshavebettercouplingefficiencythansurface emitter.
- ELEDsaretemperature sensitive.

Usage:

1. LEDsaresuitedforshortrangenarrowand mediumbandwidth links.
2. Suitablefordigital systemsupto140 Mb/sec.
3. Longdistanceanaloglinks

LightSourceMaterials

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

Direct bandgap semiconductors.

Indirectbandgapsemiconductors.

Somecommonlyusedbandgapsemiconductorsareshowninfollowingtable3.1.1

Semiconductor	**Energybandgap(eV)**	**RecombinationBr(cm3/ sec)**
GaAs	Direct:1.43	7.21x10-10
GaAs	Direct:0.73	2.39x10-10
InAs	Direct:0.35	8.5x10-11
InSb	Direct:0.18	4.58x10-11
Si	Indirect:1.12	1.79x10-15
Ge	Indirect: 0.67	5.25x10-14
GaP	Indirect:2.26	5.37x10-14

Table3.1.1Semiconductormaterialforoptical sources

Directbandgapsemiconductorsaremostusefulforthispurpose.Indirectbandgap semiconductorstheelectronsandholesoneithersideofbandgaphavesamevalueof crystal momentum. Hence direct recombination is possible. The recombination occurs within 10-8 to 10-10sec.

In indirect bandgap semiconductors, the maximum and minimum energies occur at different valuesof crystalmomentum.Therecombinationinthesesemiconductorsisquiteslow i.e.10^{-2} and 10^{-3} sec.

The active layer semiconductor material must have a direct bandgap. In direct bandgap semiconductor, electrons and holes can recombine directly without need of third particle to conserve momentum. In these materials the optical radiation is sufficiently high. These materials are compounds of group III elements (Al, Ga, In) and group V element (P, As, Sb). Some tertiary allos Ga1-x Alx As are also used.

EmissionspectrumofGa1-xAlxAsLEDisshowninFig.3.1.6.

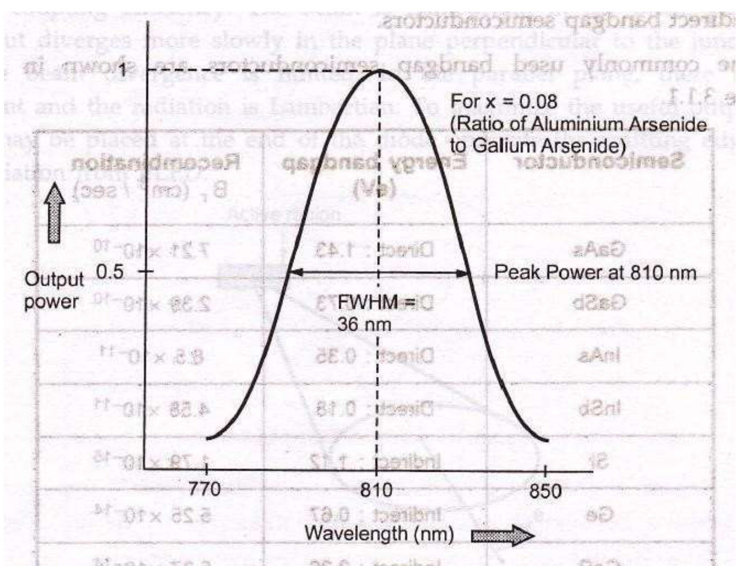


Fig. 3.1.6 Emission spectrum of $Ga_{1-x}\ Al_x$ As LED

Thepeakoutputpowerisobtainedat810nm.Thewidthofemissionspectrumathalf power (0.5) is referred as full width half maximum (FWHM) spectral width. For the givenLEDFWHMis36nm.

The fundamental quantum mechanical relationship between gap energy E and frequency
visgivenas

$$E = hv$$

$$E = h\frac{c}{\lambda}$$

$$\lambda = \frac{hc}{E}$$

where,energy(E)isinjoulesandwavelength(λ)isinmeters.Expressingthegapenergy(Eg) inelectronvoltsandwavelength(λ)inmicrometersforthis application.

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

Differentmaterialsandalloyshavedifferentbandgapenergies

The bandgap energy (Eg) can be controlled by two compositional parameters x and y, within directbandgap region.ThequartenaryalloyIn1-xGaxAsyP1-yisthe principal material sued in such LEDs. Two expression relating Eg and x,y are –

$$E_g = 1.424 + 1.266\ x + 0266\ x^2$$

$$E_g = 1.35 - 0.72\,y + 0.12\,y^2$$

Example3.1.1:Computetheemittedwavelengthfromanopticalsourcehavingx=0.07.

Solution: x=0.07

$$E_g = 1.424 + 1.266\,x + 0266\,x^2$$

$$E_g = 1.424 + (1.266\ x\ 0.07) + 0266\ x\ (0.07)^2$$

Eg= 1.513 eV

now

$$\boxed{\lambda = \frac{1.24}{E_g}}$$

$$\lambda = \frac{1.24}{1.513}$$

$$\lambda = 0.819\ \mu m$$

$$\lambda = \mathbf{0.82}\ \mu\mathbf{m}$$

Example3.1.2:ForanalloyIn0.74Ga0.26As0.57P0.43tobesuedinLed.Findthe wavelength emitted by this source.

Solution :Comparing the alloy with the quartenary alloy composition. In1-x Gax As P1-y it is found that

x= 0.26and y=0.57

Eg =1.35–0.72y +0.12y2

Using

Eg= 1.35-(0.72 x0.57)+0.12x0.572

Eg = 0.978eV

now

$$\lambda = \frac{1.24}{E_g}$$

$$\lambda = \frac{1.24}{0.978}$$

$$\lambda = 1.2671\ \mu m$$

$$\lambda = \mathbf{1.27\ \mu m}$$

QuantumEfficiencyandPower

The internal quantum efficiency (ηint) is defined as the ratio of radiative recombination rate to the total recombination rate.

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

Where,

Rrisradiativerecombinationrate.

Rnrisnon-radiativerecombinationrate.

$$\tau_r = \frac{n}{R_r}$$

Ifnaretheexcesscarriers,thenradiativelifetime,andnon-radiativelifetime,

$$\tau_r = \frac{n}{R_{nr}}$$

Theinternal quantum efficiencyisgivenTherecombinationtime ofcarriersinactiveregionis τ.Itisalsoknownasbulkrecombinationlifetime.

$$\eta_{int} = \frac{1}{1 + \frac{R_{nr}}{R_r}}$$

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

$$\eta_{int} = \frac{1}{1 + \frac{\tau_r}{\tau_{nr}}}$$

Thereforeinternalquantumefficiencyisgivenas–

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

IfthecurrentinjectedintotheLEDisIandqiselectronchargethentotalnumberofre combinations per second is –

$$R_r = R_{nr} = \frac{I}{q}$$

$$\eta_{int} = \frac{R_r}{I / q}$$

$$R_r = \eta_{int} \, x \, \frac{I}{q}$$

OpticalpowergeneratedinternallyinLEDisgivenas–

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

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

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

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

Not all internally generated photons will available from output of device. The external quantumefficiencyisusedtocalculatetheemittedpower.Theexternalquantumefficiencyis defined as the ratio of photons emitted from LED to the number of photons generated internally. It is given by equation

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

TheopticaloutputpoweremittedfromLED isgivenas–

$$P = \eta_{ext} . P_{int}$$

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

Example 3.1.3 : The radiative and non radiative recombination life times of minority carriers in the active region of a double heterojunction LED are 60 nsec and 90 nsec respectively.Determinethetotalcarrierrecombinationlifetimeandoptical powergenerated internally if the peak emission wavelength si 870 nm and the drive currect is 40 mA.

Solutions:

Given: λ =870nm0.87x10-6 m

τr = 60 nsec.

τnr=90nsec.

I=40mA=0.04Amp.

i) Totalcarrierrecombinationlifetime:

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

$$\frac{1}{\tau} = \frac{1}{60} + \frac{1}{90}$$

$$\frac{1}{\tau} = \frac{150}{5400}$$

ii) Internalopticalpower

iii)
$$P_{int} = \eta_{int} \cdot \frac{hc\, I}{q\lambda}$$

iv)
$$P_{int} = \left(\frac{\tau}{\tau_r}\right)\left(\frac{hc\, I}{q\lambda}\right)$$

$$P_{int} = \left(\frac{30}{60}\right)\left[\frac{(6.625 \times 10^{-34})(3 \times 10^{8}) \times 0.04}{(1.602 \times 10^{-19})(0.87 \times 10^{-6})}\right]$$

Example 3.1.4 : A double heterjunciton InGaAsP LED operating at 1310 nm has radiative and non-radiative recombination times of 30 and 100 ns respectively. The current injected is 40 Ma.

Calculate–Bulkrecombinationlifetime.InternalquantumefficiencyInternalpowerlevel.

Solution:λ =1310nm=(1.31x10-6m)

τr = 30 ns

τnr=100ns

i) I=40MA –0.04Amp.

BulkRecombinationLifetime(τ):

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

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

Internalquantumefficienty(ηint)

$$\eta_{int} = \frac{23.07}{30}$$

$$\eta_{int} = \mathbf{0.769}$$

Internalpowerlevel(Pint):

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

AdvantagesandDisadvantagesofLED

Advantages of LED

ii) Simpledesign.

iii) Ease of manufacture.

iv) Simplesystemintegration.

v) Lowcost.

vi) High reliability.

Disadvantagesof LED

1. Refractionoflightatsemiconductor/airinterface.
2. Theaveragelifetimeof aradiativerecombinationisonlyafewnanoseconds,therefore
3. ModulationBWislimitedtoonlyfewhundredmegahertz.
4. Lowcouplingefficiency.
5. Largechromatic dispersion.

ComparisonofSurfaceandEdgeEmittingLED

LEDtype	Max.modulationfreq. (MHz)	Outputpower(mW)	Fibercoupledpower
Surface emitting	60	<4	<0.2
Edgeemitting	200	<7	<1.0

InjectionLaserDiode(ILD)

The laser is a device which amplifies the light, hence the LASER is an acronym for light amplification by stimulated emission of radiation.

The operation of the device may be described by the formation of an electromagnetic standingwavewithinacavity(opticalresonator)whichprovidesanoutputof monochromatic highly coherent radiation.

Principle:

Material absorb light than emitting. Three different fundamental process occurs between the two energystates of an atom. Absorption 2) Spontaneous emission 3) Stimulated emission.Laser action is the result of three process absorption of energy packets (photons) spontaneous emission, and stimulated emission. (These processes are represented by the simple two-energy-level diagrams). Where E_1 is the lower state energy level. E_2 is the higher state energy level.

Quantum theory states that any atom exists only in certain discrete energy state, absorption or emission of light causes them to make a transition from one state to another. The frequency of the absorbed or emitted radiation f is related to the difference in energy E between the two states. If E_1 is lower state energy level. and E_2 is higher state energy level

$E = (E_2 - E_1) = h.f$.Where, $h = 6.626 \times 10^{-34}$ J/s (Planck's constant).

Anatomisinitiallyin thelowerenergystate,whenthephotonwithenergy($E_2 - E_1$)is incident on the atom it will be excited into the higher energy state E_2 through the absorption of the photon

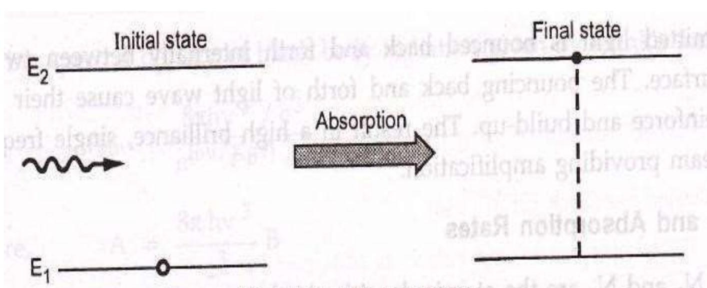


Fig. 3.1.7 Absorption

WhentheatomisinitiallyinthehigherenergystateE2,itcanmakeatransitiontothelower energystateE1providingtheemission ofaphotonatafrequencycorrespondingto [illegible]=h.f. The emission process can occur in two ways. By spontaneous emission in which the atom returns to the lower energy state in random manner.

By stimulated emission when a photon having equal energy to the difference between the two states (E2 – E1) interacts with the atom causing it to the lower state with the creation of the second photon

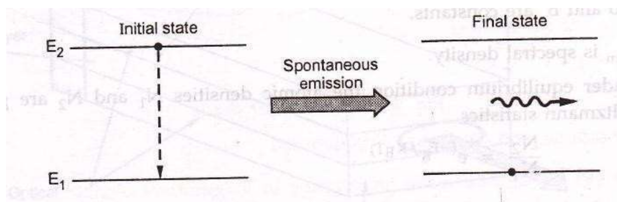


Fig. 3.1.8 Spontaneous emission

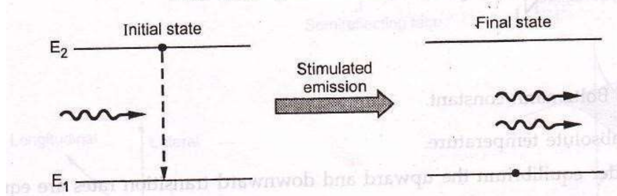


Fig. 3.1.9 Stimulated emission

Spontaneous emission gives incoherent radiation while stimulated emission gives coherent radiation. Hence the light associated with emitted photon is of same frequency of incident photon, and in same phase with same polarization.

It means that when an atom is stimulated to emit light energy by an incident wave, the liberated energy can add to the wave in constructive manner. The emitted light is bounced backandforthinternallybetweentworeflectingsurface. Thebouncingbackandforthoflight wavecausetheirintensitytoreinforceandbuild-up.Theresultinahighbrilliance,single frequency light beam providing amplification.

EmissionandAbsorptionRates

ItN1andN2aretheatomicdensitiesinthegroundandexcited states.

Rateofspontaneousemission

Rspon=AN2

Rateofstimulatedemission

Rstim = BN2 ρem

Rateofabsorption

Rabs = B’ N1 ρem

where,

A,BandB’areconstants.

ρem is spectral density.

Underequilibriumconditiontheatomicdensities N1andN2aregivenbyBoltzmann statistics.

$$\frac{N_2}{N_1} = eg^{(-E_B\,/\,K_BT)}$$

$$\frac{N_2}{N_1} = eg^{(-h_v\,/\,K_BT)}$$

where,

KB is Boltzmann constant.

Tisabsoluteтemperature.

Underequilibriumtheupwardanddownwardtransitionratesare equal.

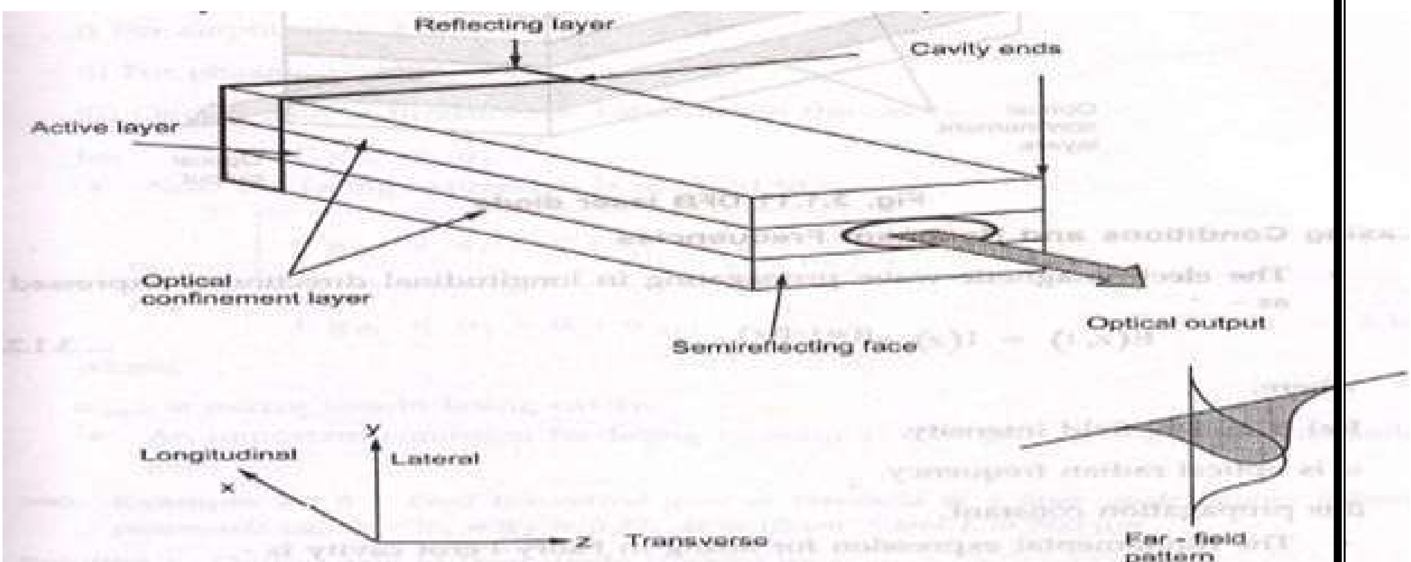
AN2 +BN2ρem=B’N1ρem

Spectraldensitypem

Comparingspectral densityofblackbodyradiationgivenbyPlank'sformula, Therefore, …A and B are called Einstein's coefficient.

Fabry–Perot Resonator

Lasers are oscillators operating at frequency. The oscillator is formed by a resonant cavity providing a selective feedback. The cavity is normally a Fabry-Perot resonator i.e. two parallel plane mirrors separated by distance L,



Light propagating along the axis of the interferometer is reflected by the mirrors back to the amplifying medium providing optical gain. The dimensions of cavity are 25-500 µm longitudinal 5-15 µm lateral and 0.1-0.2 µm transverse. Fig. 3.1.10 shows Fabry-Perot resonator cavity for a laser diode.

The two heterojunctions provide carrier and optical confinement in a direction normal to the junction. The current at which lasing starts is the threshold current. Above this current the output power increases sharply.

DistributedFeedback(DFB)Laser

In DFB laster the lasing action is obtained by periodic variations of refractive index along the longitudinal dimension of the diode. Fig. 3.1.11 shows the structure of DFB laser diode

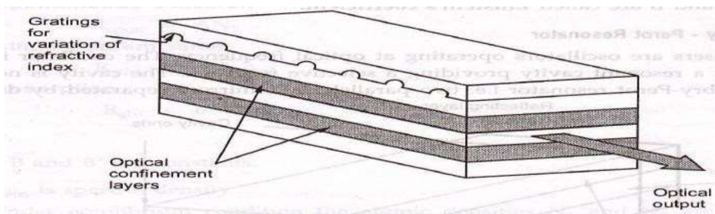


Fig. 3.1.11 DFB laser diode

Lasingconditionsandresonant Frequencies

Theelectromagneticwavepropagatinginlongitudinaldirectionisexpressedas – E(z, t)

= I(z) ej(ω t-β z)

where,

I(z)isopticalfieldintensity.

isopticalradianfrequency. β

is propagation constant.

ThefundamentalexpressionforlasinginFabry-Perotcavityis–

$$I(z) = I(0)e^{[\{\Gamma g(h v) - \alpha(h v)\}z]}$$

where,isopticalfieldconfinementfactororthefractionofopticalpowerintheactivelayer.

αiseffectiveabsorptioncoefficientofmaterial.

gisgain coefficient.

hvisphoton energy.

z isdistance traverses alongthelasing cavity.

Theconditionoflasingthresholdisgivenas – For

amplitude : I (2L) = I (0)

For phase: e-j2βL=1

Opticalgainatthreshold=Totallossinthecavity.

i.e.Γgth =αt

Nowthelasingexpressionisreducedto–

$$\Gamma g_{th} = a_t = \propto + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right)$$

$\Gamma g_{th} = \propto_t = \propto + \propto_{end}$

where,

Aendismirrorlossinlasingcavity.Animportantconditionforlasingtooccuristhatgain,g≥

gthi.e.thresholdgain.

Example3.1.5:Findtheopticalgainatthresholdofalaserdiodehavingfollowing parametricvalues – R1 = R2 = 0.32, α = 10cm-1 and L = 500 µm.

Solution: Opticalgaininlaser diodeisgivenby–

$$\Gamma g_{th} = 10 + \frac{1}{2 \times (500 \times 10^{-4})} \ln\left(\frac{1}{0.32 \times 0.32}\right)$$

$$\Gamma g_{th} = 33.7 \text{ cm}^{-1}$$

PowerCurrentCharacteristics

The output optic power versus forward input current characteristics is plotted in Fig. 3.1.12 for a typical laser diode. Below the threshold current (Ith) only spontaneous emission is emitted hence there is small increase in optic power with drive current. At threshold when lasing conditions are satisfied. The optical power increases sharply after the lasing threshold because of stimulated emission.The lasing threshold optical gain (gth) is related by threshold current density (Jth) for stimulated emission by expression –

g th=β

where,βisconstantfordevicestructure

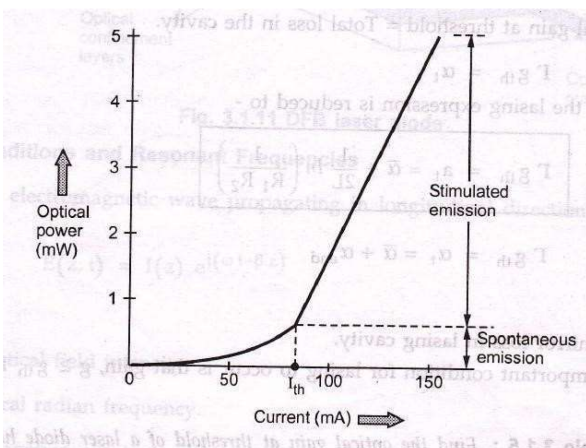


Fig. 3.1.12 Power current characteristics

Fig.3.1.12Powercurrentcharacteristics

ExternalQuantumEfficiency

The external quantum efficiency is defined as the number of photons emitted per electron hole pair recombination above threshold point. The external quantum efficiency ηext is given by –

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

where,

ηi=Internalquantumefficiency(0.6-0.7). gth

= Threshold gain.

α=Absorptioncoefficient

Typicalvalueofηextforstandardsemiconductorlaserisrangingbetween15-20%.

ResonantFrequencies

Atthresholdlasing

2β L =2π m

where,(propagationconstant) m

is an integer.

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

Since c =vλ

$$\lambda = \frac{c}{v}$$

Substitutingλin3.1.30

$$m = 2L\,\frac{nv}{c}$$

Gain inanylaserisafunction offrequency.ForaGaussianoutputthegainandfrequency are related by expression –

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

where,g(0)ismaximumgain.λ0iscenterwavelengthinspectrum.isspectralwidthofthe gain.Thefrequencyspacingbetweenthetwosuccessivemodesis–

$$\Delta v = \frac{c}{2\,L\,n}$$

$$\Delta \lambda = \frac{\lambda^2}{2\,L\,n}$$

OpticalCharacteristicsofLEDandLaser

The output of laser diode depends on the drive current passing through it. At low drive current,thelaseroperatesasaninefficientLed,Whendrivecurrentcrossesthresholdvalue, lasing action beings. Fig. 3.1.13 illustrates graph comparing optical powers of LED operation (due to spontaneous emission) and laser operation (due to stimulated emission).

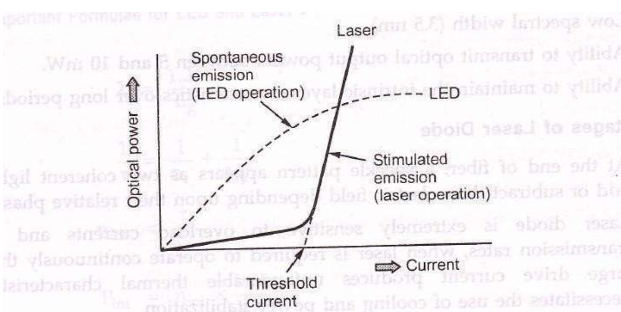


Fig. 3.1.13 Optical characteristics of an LED and laser compared

SpectralandSpatialDistributionofLedandLaser

AtlowcurrentlaserdiodeactslikenormalLEDabovethresholdcurrent,stimulatedemission i.e. narrowing of light ray to a few spectral lines instead of broad spectral distribution, exist. This enables the laser to easily couple to single mode fiber and reduces the amount of uncoupled light (i.e. spatial radiation distribution). Fig. 3.1.14 shows spectral and spatial distribution difference between two diodes

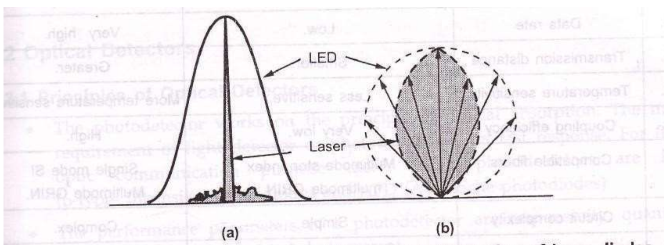


Fig. 3.1.14 Comparing (a) spectral and (b) spatial distribution of laser diodes

AdvantagesandDisadvantagesofLaserDiode

Advantages of Laser Diode

- Simpleeconomicdesign.
- Highoptical power.
- Productionoflightcanbepreciselycontrolled.
- Canbeusedathigh temperatures.

- Bettermodulationcapability.
- Highcouplingefficiency.
- Low spectralwidth(3.5nm)
- Abilitytotransmitopticaloutputpowersbetween5and10mW.
- Abilitytomaintaintheintrinsiclayercharacteristicsoverlong periods.

DisadvantagesofLaser Diode

- Attheendoffiber,aspecklepatternappearsastwocoherentlightbeamsaddor subtract their electric field depending upon their relative phases.
- Laser diodeis extremelysensitivetooverload currentsand at high transmission rates, when laserisrequiredtooperatecontinuouslythe useoflargedrivecurrentproduces unfavourable thermal characteristics and necessitates the use of cooling and power stabilization.

ComparisonofLEDandLaserDiode

S.No.	Parameter	LED	LD(Laser Diode)
1	Principleofoperation	Spontaneousemission.	Stimulatedemission.
2	Output beam	Non–coherent	Coherent.
3	Spectral width	Boardspectrum(20nm – 100 nm)	Much narrower (1-5 nm).
4	Datarate	Low.	Very high.
5	Transmissiondistance	Smaller.	Greater.
6	Temperaturesensitivity	Lesssensitive.	More temperature

			sensitive
7	Couplingefficiency	Very low.	High.
8	Compatiblefibers	Multimodestepindexmultimode GRIN	Single mode SI MultimodeGRIN
9	Circuitcomplexity	Simple	Complex
10	Lifetime	105 hours.	104 hours.
11	Cost	Low.	High.
12	Outputpower	Linearly proportional to drive current	Proportionaltocurrent abovethe threshold
13	Current required	Drivecurrent 50to100mA peak.	Thresholdcurrent5to 40ma
14	Applications	Moderatedistancelowdatarate.	Longdistancehigh data rates.

ImportantFormulaeforLEDandLaser

LED

- $\lambda = \frac{1.24}{E_g}$
- $\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$
- $\eta_{int} = \frac{\tau}{\tau_r}$

- $P_{int} = \eta_{int} \times \frac{hc\,I}{q\lambda}$

LASER

1. $\Gamma\, g_{th} = \propto + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right)$
2. $\Delta v = \frac{c}{2\,L\,n}$
3. $\Delta \lambda = \frac{\lambda^2}{2\,L\,n}$

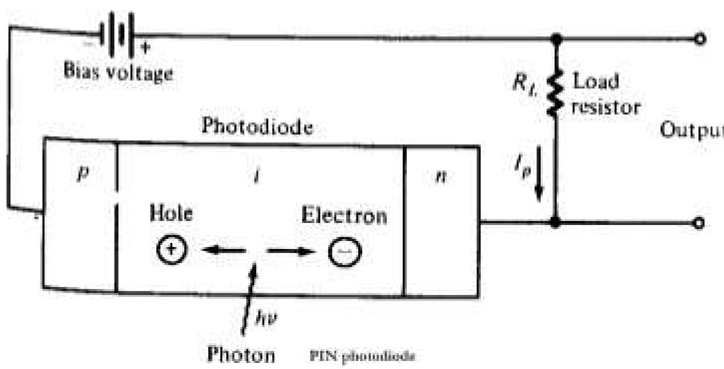
UNITIV

OPTICALDETECTORSANDRECEIVERS

- Thephoto-diodeisinfactap-n junctionputtothe exactoppositeuseasthe LED
- Thevariationincurrentisafunctionoftheincident light
- Useofthestimulatedabsorptionoflightbythesemiconductormaterialforthe generation of electron-hole pairs.
- The energy of the absorbed photons to transfer the electrons from the ground to the excited state contributes to the variation in circuit current.
- Theenergyoftheabsorbedphotonmustatleastbeequaltotheband-gapofthe material for the material to respond to the incoming photons.

PINdiode

- A simple wayto increase the depletion-region width isto insert alayer ofundoped (or lightly doped) semiconductor material between the p–n junction.
- Since the middle layer consists of nearly intrinsic material, such a structure is referred to as the p–i–n photodiode.



PIN photodiode

Figure 3.11

- When photon enters photodetector, the low band gap absorption layer absorbs the photon, and an electron-hole pair is generated. This electron hole pair is called photocarrier.
- These photocarriers, under the influence of a strong electric field generated by a reverse bias potential difference across the device as shown in figure produce photocurrent proportional to number of incident photons.

AvalanchePhotoDiode(APD)

- Alldetectorsrequireacertainminimumcurrenttooperatereliably.Thecurrent requirement translates into a minimum power requirement through Pin=IpRPin=IpR.
- DetectorswithalargeresponsivityRarepreferredsincetheyrequirelessoptical power.
- The responsivity of p–i–n photodiodes is limited while Avalanche photodiode (APDs) can have much larger values of R.

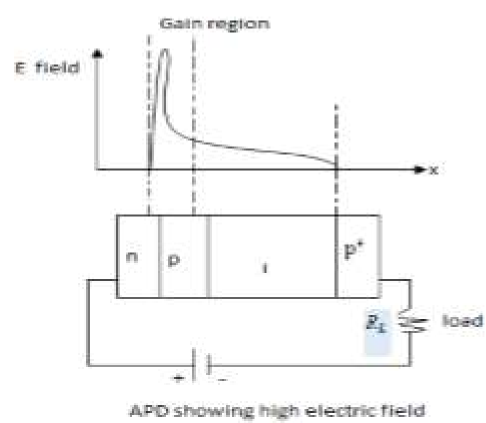


Figure 3.12: APD

WorkingofAPD

- APD is similar to PIN diode the exception is the addition of high intensity electric field region.
- In this regionprimary electronholepairsare generated bytheincidentphotonswhich are able to absorb enough kinetic energy from strong electric field to collide with the atoms present in this region, thus generating more electron hole pairs.
- The physical phenomenon behind the internal current gain is known as the impact ionization.
- This impact ionization leads to avalanche breakdown in ordinary reverse bias. It requires very high reverse bias voltage in order that the new carriers created by impact ionization can themselves produce additional carriers by same mechanism.
- This process of generating more than one electron hole pair from incident photon through ionization process is referred to as the avalanche effect.
- Thustheavalanchemultiplicationresultsinamplificationofphotodiode current.
- Multiplication factor: Multiplication factor Mis ameasureof internal gainprovidedby APD. It is defined as the ratio of total multiplied output current to the primary un multiplied current.

M=IIpM=IIp

WhereItheTotalmultipliedoutputcurrent

IpIp is the primary un multiplied current

Multiplicationdependsonphysicalandoperationalcharacteristicsofphotodetectordevice. Operational characteristics include the width of avalanche region, the strength of electric field and type of semiconductor material employed.

Comparison:

Sr no.	PINdiode	APD(Avalanche photodiode)
1	PIN does not have high intensityelectricfieldregion.	APDhashighintensityelectricfieldregion.
2	Photocurrent(IpIp)generated is less compared to APD Ip=qNθ, q=electroncharge, Nθ=carriernumber	Photocurrent(IpIp)generatedismorecomparedtoPIN, Ip=qNθ.M q=electroncharge, Nθ=carrier number, M=multiplicationfactor
3	ResponsivelyofPINislimited.	ResponsivelyofAPDcanhavemuchlargervalues.
4	Theyexhibitlowernoiselevels.	TheyexhibithighernoiselevelsascomparedtoPINdue to impact ionization and photocurrent multiplication.
5	ResponsetimeofPINishalf that of APD.	Responsetimeof APDisalmostdoublethatofPIN.

The PIN-diode is an alteration of the PN-junction for particular applications. After the PN-junction diodewas developed in the year 1940s, the diode was first exercised as a high- power rectifier, low-frequency during the year 1952. The occurrence of an intrinsic layer can significantly increase the breakdown voltage for the application of high-voltage.This intrinsic layer also offers exciting properties when the device operates at high frequencies in therange of radio wave and microwave. A PIN diode is a one kind of diode with an undoped,wideintrinsicsemiconductorregionbetweenaP-typeandN-typesemiconductor region. These regions are normally heavily doped as they are used for Ohmic contacts. The widerintrinsic regionis indifferencetoan ordinary p–ndiode.This regionmakes thediode an inferior rectifier but it makes it appropriate for fast switches, attenuators, photo detectors and high voltage power electronics applications.

The PIN diode is a one type of photo detector, used to convert optical signal into an electrical signal. The PIN diode comprises of three regions, namely P-region, I-region and N-region. Typically, both the P and N regions are heavily doped due to they are utilized for Ohmic contacts. The intrinsic region in the diode is in contrast to a PN junction diode. This region makes the PIN diode a lower rectifier, but it makes it appropriate for fast switches, attenuators, photo detectors and applications of high voltage power electronics.

Photodetectors:

These are Opto-electric devices i.e. to convert the optical signal back into electrical impulses. The light detectors are commonly made up of semiconductor material. Photo detectors made up of semiconductormaterial.Whenthelightstrikesthelightdetectoracurrentisproducedintheexternal circuit proportional to the intensity of the incident light.

Opticalsignalgenerallyisweakenedanddistortedwhenitemergesfromtheendofthefiber, the photo detector must meet following strict performance requirements.

- Ahighsensitivitytotheemissionwavelengthrangeofthereceivedlightsignal
- Aminimumadditionofnoisetothesignal
- Afastresponsespeedtohandlethedesireddatarate
- Beinsensitivetotemperaturevariations
- Becompatiblewiththephysicaldimensionsofthe fiber
- HaveaReasonablecostcomparedtoothersystemcomponents
- Havealongoperating lifetime

Someimportantparameterswhilediscussingphotodetectors:

QuantumEfficiency

It is the ratio of primary electron-hole pairs created by incident photon to the photon incident on the diode material.

Detector Responsivity

This is the ratioof output current to inputoptical power.Hence this is theefficiency of the device.

SpectralResponse Range

Thisistherange ofwavelengthsoverwhichthedevicewilloperate.

Noise Characteristics

Thelevelofnoiseproduced inthedeviceiscriticaltoitsoperationatlowlevelsofinputlight.

ResponseTime

Thisisameasureofhowquicklythedetectorcanrespondtovariationsintheinputlight intensity.

TypesofLight Detectors

- PINPhotodiode

- AvalanchePhotodiode

PIN photodiode

InGaAsavalanchephotodiode

Photodetectormaterials

OperatingWavelengthRangesforSeveralDifferentPhotodetectorMaterials

Material	Energy gap, eV	λ_{cutoff}, nm	Wavelength range, nm
Silicon	1.17	1060	400–1060
Germanium	0.775	1600	600–1600
GaAs	1.424	870	650–870
InGaAs	0.73	1700	900–1700
InGaAsP	0.75–1.35	1650–920	800–1650

InGaAsisusedmostcommonlyforbothlong-wavelengthpinandavalanchephotodiodes

PhysicalPrinciplesofPhotodiodes

ThePinPhotodetector

- The device structure consists of p and n semiconductorregions separated by a very lightly n-doped intrinsic (i) region.
- In normal operation a reverse-bias voltage is applied across the device so that no free electrons or holes exist in the intrinsic region.
- Incident photon having energy greater than or equal to the band gap energy of the semiconductor material, give up its energy and excite an electron from the valence band to the conduction band

PinPhotodetector

the high electric field present in the depletion region causes photogenerated carriers to separate and be collected across the reverse – biased junction. This gives rise to a current flow in an external circuit, known as photocurrent.

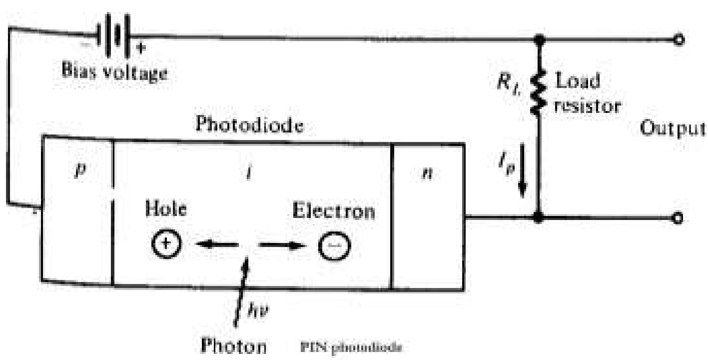


Figure 3.11

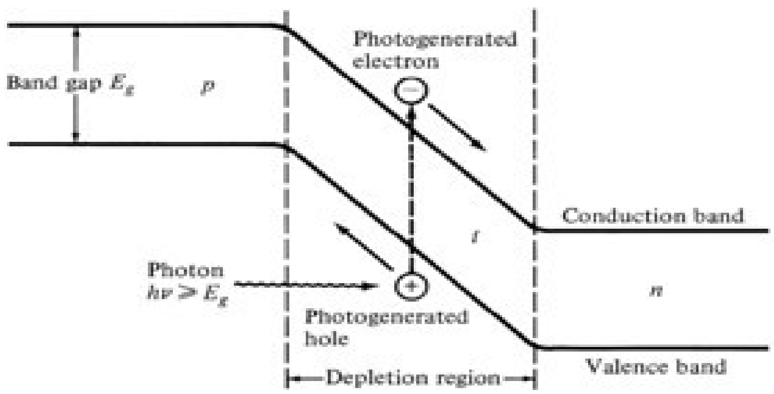
Photo carriers:

Incidentphoton,generatesfree(mobile)electron-holepairsintheintrinsicregion. Thesechargecarriersareknownasphotocarriers,sincetheyaregeneratedbya photon.

Photocurrent:

The electric field across the device causes the photocarriers to be swept out of the intrinsic region, thereby giving rise to a current flow in an external circuit. This current flow is known as the photocurrent.

Energy-Banddiagramforapinphotodiode



Anincidentphotonisabletoboostanelectrontotheconductionbandonlyifithasan energy that is greater than or equal to the bandgap energy

Beyondacertainwavelength,thelightwillnotbeabsorbedbythematerialsincethewavelength of a photon is inversely proportional to its energy

Thus,aparticularsemiconductormaterialcanbeusedonlyoveralimitedwavelengthrange.

Theupperwavelength λccutoffisdeterminedbytheband-gapenergyE gofthe material.

$$\lambda_c = \frac{hc}{E_g}$$

• Asthechargecarriersflowthroughthematerialsomeofthemrecombineanddisappear.

• ThechargecarriersmoveadistanceLnorLpforelectronsandholesbeforerecombining.This distanceisknownasdiffusionlength

• Thetimeittaketorecombineisitslifetimeτnorτprespectively.

L n=(Dnτn)1/2andL p=(Dpτp)1/2

• WhereDnandDparethediffusioncoefficientsforelectronsandholesrespectively.

Photocurrent

• Asaphotonfluxpenetratesthroughthesemiconductor,itwillbeabsorbed.

• IfPinistheopticalpowerfallingonthephotodetectoratx=0andP(x)isthepowerlevelata distance x into the material then the incremental change be given as

$$dP(x) = -\alpha_s(\lambda)P(x)dx$$

Whereαs(λ)isthephotonabsorptioncoefficientatawavelengthλ.

Sothat

$$P(x) = P_{in}\exp(-\alpha_s x)$$

• Opticalpowerabsorbed,P(x),inthedepletionregioncanbewrittenintermsofincidentoptical power, Pin :

$$P(x) = P_{in}(1 - e^{-\alpha_s(\lambda)x})$$

• Absorptioncoefficientαs(λ)stronglydependsonwavelength.Theupperwavelengthcut-offforany semiconductor can be determined by its energy gap as follows:

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

• Takingentrancefacereflectivityintoconsideration,theabsorbedpowerinthewidthofdepletion region, w, becomes:

$$(1-R_f)P(w) = P_{in}(1-e^{-\alpha_s(\lambda)w})(1-R_f)$$

DetectorResponseTime

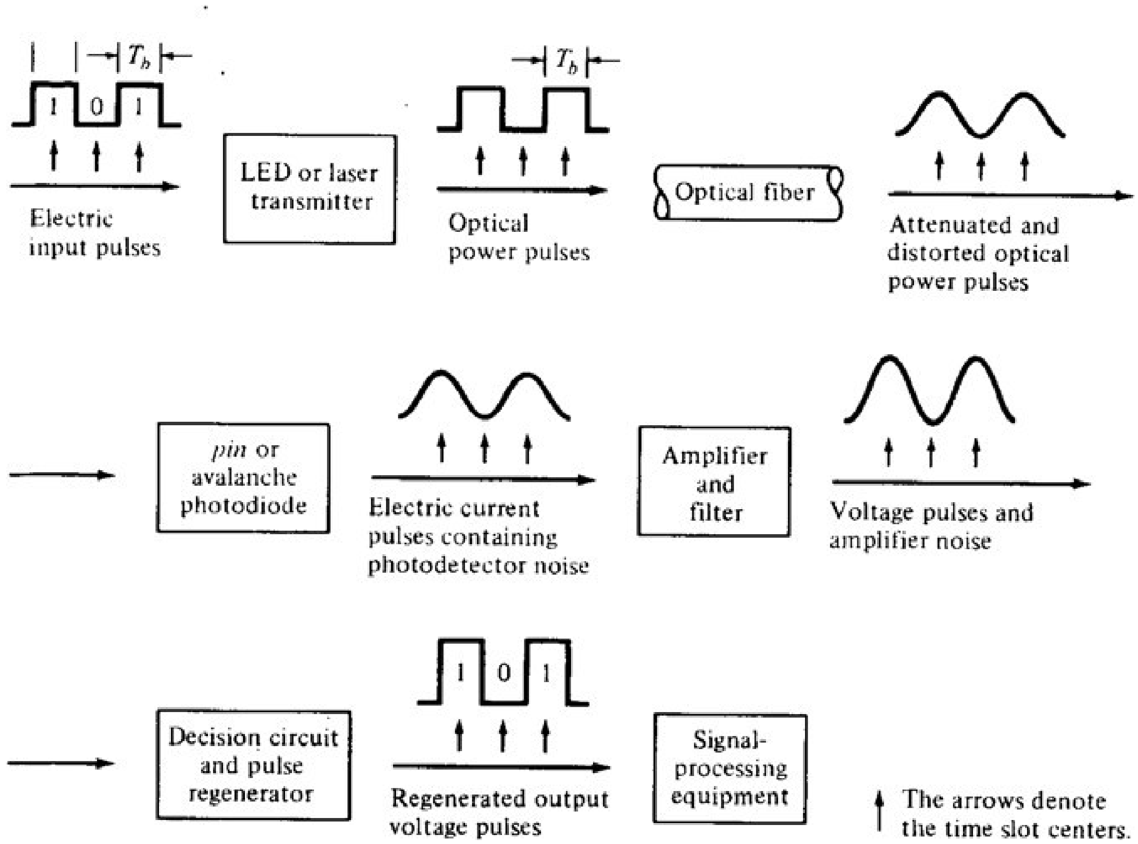
Theresponsetimeofphotodiodetogetherwithitsoutputcircuitdependsmainlyonthe following three factors:

1. Thetransittimeofthephotocarriersinthedepletion region.
2. Thediffusiontimeofthephotocarriersgeneratedoutsidethedepletionregion.
3. TheRCtimeconstantofthephotodiodeanditsassociatedcircuit.

S.No	Parameters	PIN	APD
1	Sensitivity	Less sensitive(0-12dB)	More sensitive(5-15dB)
2	Biasing	Low reverse biased voltage(5to 10V)	Highreverse biased voltage (20-400volts)
3	Wavelength region	300-1100 nm	400-1000 nm
4	Gain	NoInternal gain	Internalgain

OpticalReceiverDesign

The receiver mustfirstdetectweak, distorted signal and then makedecisions on what type of data was sent based on amplified version of the distorted signal. To understand the function of the receiver,we first examine what happens to the signal as it is sent through the optical data link which is shown in the following figure



A digital fiber transmission link is shown in the above figure. The transmitted signal isa two level binary data stream consisting of either a 0 or 1 in a time slot of duration T_b. This time slot is referred to as bit period. Electrically there are many ways of sending a givendigital message. One of the simplest techniques for sending binary data is **Amplitude Shift Keying (ASK),** wherein avoltage level is switched between twovalues,which are generally on and off. The resultant signal wave thus consists of a voltage pulse of amplitude V relative to zero voltage level when a binary 1 occurs and a zero voltage level space when a binary 0 occurs. When a 1 is sent, a voltage pulse of duration $T_b$occurs, whereas for a 0 the voltage remains at its zero level.

The function of the optical transmitter is to convert the electric signal to an optic signal. Here 1 is represented by a pulse of optical power (light) of duration T_b whereas a 0 is the absence of any light. The optical signal that gets coupled from the light source to the fiber becomes attenuated and distorted as it propagates along the fiber waveguide. Upon reaching the receiver either a pin or an avalanche photodiode converts the optical signal back to anelectric format. The electric signal then gets amplified and filtered. A decision circuitcompares

The signal in each time slot with a certain reference voltage known as the threshold level. If the received signal level is greater than the threshold level, a 0 is assumed to be received. In some cases an optical amplifier is placed ahead of the photodiode to boost the optical signal level before photodetection. This is done so that the signal to noise ratio degradation caused by thermal noise in the receiver electronics can be suppressed. Compared to APD’s or optical heterodyne detectors, an optical preamplifier provides a large gain factor and a broader bandwidth.

<u>ErrorSources:</u>

Errors arise from various noise and disturbances associated with the signal detection system which is shown in the following figure.

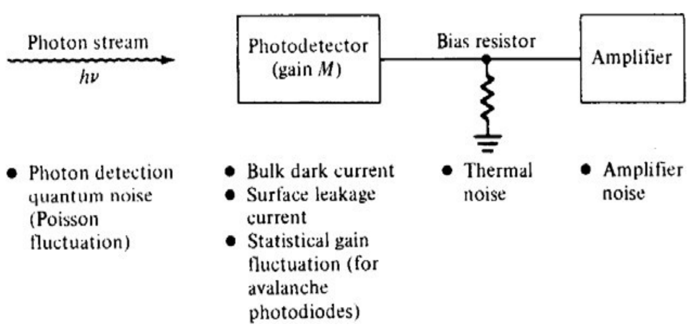


Fig:Noisesourcesanddisturbancesintheopticalpulsedetectionmechanism.

Anopticalreceiversystemconvertsopticalenergyintoelectricalsignal,amplifythesignaland process it. Therefore the important blocks of optical receiver are

- Photodetector/ Front-end
- Amplifier/Liner channel
- Signalprocessingcircuitry/Datarecovery.

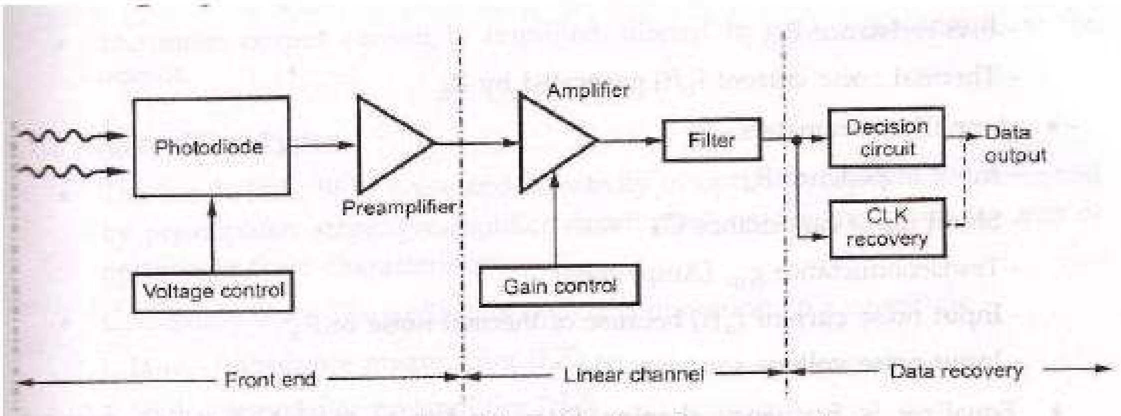


Fig. 5.1.1 Optical receiver

Noisegeneratedinreceivermustbecontrolledpreciselyasitdecidesthelowestsignal levelthatcanbedetectedandprocessed.Hencenoiseconsiderationisanimportantfactorin receiver design. Another important performance criteria of optical receiver is average error probability.

ReceiverConfiguration

ConfigurationoftypicalopticalreceiverisshowninFig

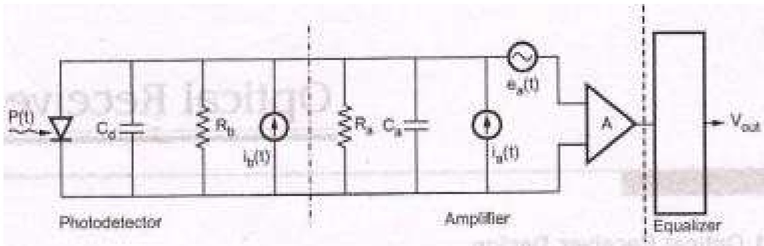


Fig. 5.1.2 Optical receiver configuration

UNIT-VOPTICAL

SYSTEM DESIGN

SYSTEMDESIGNFACTORS

To achieve high-quality transmission, careful decisions based on operating parameters apply for each component of a fiber optic transmission system. The main questions, given in Table 10.1, involve data rates and bit error rates in digital systems, bandwidth, linearity, and signal-to-noise ratios in analog systems, and in all systems, transmission distances. These questions of how far, how good, and how fast define the basic application constraints. Once these are decided, it is time to evaluate the other factors involved.

Table:FactorsforEvaluatingFiberOpticSystemDesign

SystemFactor	Consideration/Choices
TypeofFiber	Single-modeorMultimode
Dispersion	RegeneratorsorDispersionCompensation
Fiber Nonlinearities	Fiber Characteristics, Wavelengths, and Transmitter Power
OperatingWavelength	780,850,1310,1550nm, and1625nm typical.
TransmitterPower	Typicallyexpressedin dBm.
SourceType	LED orLaser
Receiver Sensitivity/Overload Characteristics	Typicallyexpressedin dBm.
DetectorType	PIN Diode,APD,or IDP

SystemFactor	Consideration/Choices
ModulationCode	AM,FM,PCM,or Digital
BitErrorRate(BER)(DigitalSystemsOnly)	10^{-9},10^{-12}Typical
Signal-to-NoiseRatio	Specifiedindecibels(dB).
NumberofConnectors	Lossincreaseswiththenumberofconnectors.
NumberofSplices	Lossincreaseswiththenumberofsplices.
EnvironmentalRequirements	Humidity,Temperature,ExposuretoSunlight
MechanicalRequirements	Flammability,Indoor/OutdoorApplication

Many of these considerations are directly related to other considerations. For example, detector choice will impact the receiver sensitivity which will affect the necessary transmitter output power. Output power impacts the transmitter light emitter type which will affect the usable fiber type and connector type. A logical way to proceed with designing a fiber link involves analyzing the fiber optic link power budget or optical link loss budget.

SYSTEMDESIGNCONSIDERATIONS:

Inopticalsystemdesignmajorconsideration involves

1. Transmissioncharacteristicsoffiber(attenuation&dispersion).
2. Informationtransfercapabilityoffiber.
3. Terminalequipment&technology.
4. Distanceof transmission.

Anopticalcommunicationsystemshouldhavefollowingbasicrequiredspecifications

- Transmissiontype(Analog/digital).
- Systemfidelity(SNR/BER)
- Requiredtransmissionbandwidth

- Acceptablerepeaterspacing
- Cost ofsystem
- Reliability
- Cost ofmaintenance.

SYSTEMCONSIDERATION:

Before selecting suitable components, the operating wavelength for the system is decided. The operating wavelength selection depends on the distance and attenuation. For shorter distance,the800-900 nm region ispreferred but for longerdistance 100or 1550nm regionis preferred due to lower attenuations and dispersion.

Thenextstepisselectionofphotodetector.Whileselectingaphotodetectorfollowing factors are considered –

- MinimumopticalpowerthatmustfallonphotodetectortosatisfyBERat specified datarate.
- Complexityof circuit.
- Cost ofdesign.
- Biasrequirements.

Nextstepinsystemconsiderationischoosingaproperopticalsource;
Important factors to consider are –

- Signal dispersion.
- Datarate.
- Transmissiondistance.
- Cost.
- Opticalpowercoupling.
- Circuitcomplexity.

The last factor in system consideration is to selection of optical fiber between single mode and Multimode fiber with step or graded index fiber. Fiber selection depends on typeof optical source and tolerable dispersion.

Someimportantfactorsforselectionoffiberare:

- NumericalAperture(NA),asNAincreases,thefibercoupledpowerincreasesalsothe Dispersion.
- Attenuationcharacteristics.
- Environmentalinducedlossese.g.duetotemperaturevariation,moistureanddust etc.

Operatingwavelengthselection:

- Firstgenerationopticalwavelengthareintherangeof0.8μmto0.9μm. Here the transmission less is maximum and dispersion is also maximum.
- Todaywechoosethewavelengtharound1.3μmto1.55μm.Herethe attenuationand dispersion are very small in silica fibers are used for long distance transmission.

Systemperformance:

- System performance is decided by three major blocks (or) the optical fiber transmission.Theyaretransmitter,opticalfiberlinksandreceiver.The designer should choose proper light source, proper optical fiber and properphoto detector to get high bit rate and high S/N ratio.
- Regardingopticalfiber,thesinglemodestepindexfiberistheproperchoice. Even in that to reduce dispersion proper choice of the refractive index profile is necessary.These single mode step index fibers are preferable.
- Regarding optical sources, single mode laser diodes are suitable for single modestop index fibers. For multi mode fibers, hetero junction LEDs chosen based economy.

- Regarding optical receivers, the P-i-nphotodiodesand avalanche photodiodes are preferable. Here also they should be quantum noise limited.

Themaximumtransmissiondistanceislimited bythenetlessoffibercablesuchthat $L=10/\alpha$
$\log_{10}$ (Pt/pr)
α=notloss(indB/1cm)
Pt=average power from transmitter
Pr=averagepowerdetectedatreceiver=$N_p$hvB

N_p=minimumnoofphotons/bitrequired
Hv=energy of photon
B=bitrate

COMPONENTCHOICE:

Fiber optic communications systems include componentsunfamiliar to most communications system designers, but their design is based on principles that differ little from their conventional counterparts. Link analysis is carried out in much the same way as for an electrical cable system. The chief distinction results from the increased bandwidth capability with fiber optic systems, which allows the design engineer to make different trade-offs in determining the optimum transmission format as well as source, detector, and cable types.

The system designer has many choices when selecting components for an optical fiber system. The major components choices are,

OpticalFiberTypeandParameters

Multimodeorsinglemode,size,refractiveindex,attenuation,dispersion,mode coupling, strength, joints etc.

SourceType

LaserorLED,opticalpowerlaunchedintothefiber,riseandfalltime,stability etc.,

TransmitterConfiguration

Designfordigitaloranalog,inputimpedance,supplyvoltage,dynamicrange, feedback etc.

DetectorTypeand Characteristics

PN,PINorAvalanchephotodiode,responsetime,activediameter,biasvoltage, dark current etc.

ReceiverConfiguration

Preamplifierdesign,BER,SNR,rangeetc.

Modulationand Coding

Source intensity modulation, pulse frequency modulation, PWM and PPM transmission.

Digitaltransmissionoranalogtransmission

SuchasbiphaseschemeandFMrespectively.Thesedecisionswillbetaken dependingonthesystemperformance,readyavailabilityofsuitablecomponentsandcost.

Theshortcomingsofthecomponentscanbementionedasfollows,

- LED may appear ideally suitable for analog transmission most of the LED display some degree of non-linearity in their output.
- The thermal behavior of LED and Lasers can limit their operation.Significant increase in junction temperature may cause loss of lasing and reduction in optical output power. Finite spectral width can cause pulse broadening due to material dispersion on an optical fiber communication link.

SystemDesignConsiderations

- Inopticalsystemdesignmajorconsideration involves
  - Transmissioncharacteristicsoffiber(attenuation&dispersion).
  - Informationtransfercapabilityoffiber.
  - Terminalequipment&technology.

- Distanceoftransmission.

- Inlong-haulcommunicationapplicationsrepeatersareinsertedatregular intervals as shown in Fig. 6.2.1

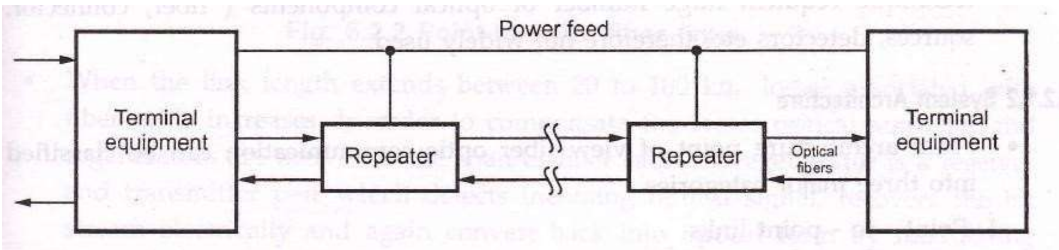


Fig. 6.2.1 Repeaters in long-haul communication system

- Repeater regenerates the original data before it is retransmitted as a digital optical signal. The cost of system and complexity increases because of installation of repeaters.
- Anopticalcommunicationsystemshouldhavefollowingbasicrequiredspecifications –

a) Transmissiontype(Analog/digital).

b) Systemfidelity(SNR/BER)

c) Requiredtransmissionbandwidth

d) Acceptablerepeaterspacing

e) Costof system

f) Reliability

g) Costof maintenance.

Multiplexing

- Multiplexing of several signals on a single fiber increases information transfer rate of communication link. In Time Division Multiplexing (TDM) pulses from multiple channels are interleaved and transmitted sequentially, it enhance the bandwidth utilization of a single fiber link.
- In Frequency Division Multiplexing (FDM) the optical channel bandwidth is dividedinto various no overlapping frequency bands and each signal is assigned one of these bands of frequencies. By suitable filtering the combined FDM signal can be retrieved.
- When number of optical sources operating at different wavelengths is to be sent on single fiber link Wavelength Division Multiplexing (WDM) is used. At receiver end, the separation or extraction of optical signal is performed by optical filters (interference filters, diffraction filters prism filters).
- Another technique called Space Division Multiplexing (SDM) used separate fiberwithin fiber bundle for each signal channel. SDM provides better optical isolation which eliminates cross-coupling between channels. But this technique requires huge numberof optical components (fiber,connector,sources,detectorsetc) thereforenot widelyused.

SystemArchitecture

Fromarchitecturepointofviewfiberopticcommunicationcanbeclassifiedintothreemajor categories.

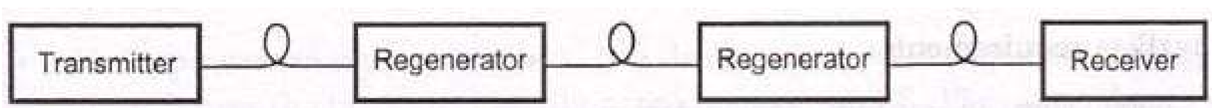
- Point –to–pointlinks
- Distributednetworks
- Localareanetworks.

Point-to-PointLinks

Apoint-to-pointlinkcomprisesofonetransmitterandareceiversystem.Thisisthesimplest form of optical communication link and it sets the basis for examining complex optical communication links.For analyzing the performance of any link following important aspects are to be considered.

- Distanceoftransmission
- Channeldatarate
- Bit-error rate

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



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

Thespacingbetweentworepeateroropticalamplifieriscalledasrepeaterspacing (L). The repeater spacing L depends on bit rate B. The bit rate-distance product (BL) is a measure of system performance for point-to-point links.

- Twoimportantanalysisfordecidingperformanceofanyfiberlinkare–

i) Linkpowerbudget/Power budget

ii) Risetimebudget/Bandwidthbudget

Point to point fiber optic lines is the simplest transmission line.This type of link places the least demand on optical fiber technology and thus sets the basis for examine more complex system architecture.

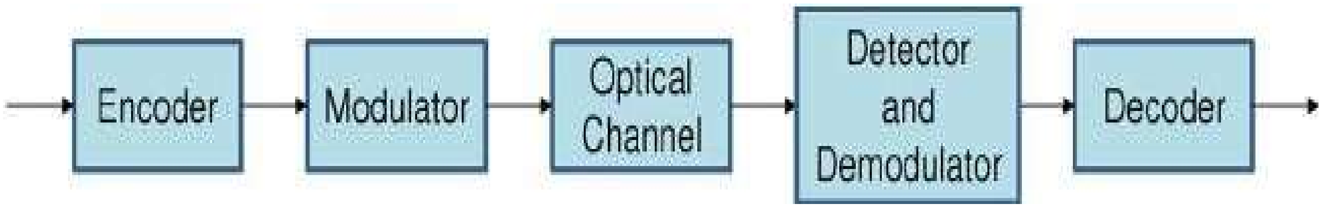


Fig:Simplepointtopoint link

The repeaters may be on to electronic (or) optical repeaters.In this system, the repeater spacingisamajordesignfactorspacingbetweenrepeaterincreases,itreducesthe systemcostspacingbetweentransmittersreceiverincreases,itwillalsoincreases system cost.(ie transmission distance **and** increases)
If L increases then bit rate reduces because of dispersion thus, product of B(bit rate) and transmission distance(L) is a measure of system performance and its depends on operating wavelength

Operating wavelength		BLproduct
0.854m		1Gb/s-Kn
1.34µm	→	1Tb/s-Km
1.55µm	→	100Tb/s-km

Toanalyzethepointtopointlink,Oneshouldknowthesystemrequirementssuchasthe maximum transmission distance, required data rate and allowed bit error rate (BER).

Tosatisfytheserequirementsthesystemshouldbedesigned based onthe components available and their characteristics.

1. Multimode(or)singlemodefiber(transmissionmedia)

(a)Core radius

(b) Fiberreactiveindex profile

(c) Bandwidth(or) dispersion

(d) Fiberattenuation

(e) Numericalaperture

2. Opticalsources(LEDorlaserdiode)

(a) Emissionwavelength

(b) Outputpower

(c) Spectrallinewidth

(d) Radiationpattern

(e) Radiatingarea

(f) no.of emittedmodes

(g) Stabilityandlifetime.

3. Lightdetectors(PIN(or)APD)

(a) Responsively

(b) Efficiencywavelength

(c) Operating

(d) Speed

(e) Sensitivity

(f) Noisefigure

LINKPOWERBUDGET:

Foroptiminglinkpowerbudgetanopticalpowerlossmodelistobestudied asshowninFig. Let

- $l_c$denotesthelossesoccuratconnector.
- L_{sp}denotesthelossesoccuratsplices.
- $\alpha_f$denotesthelossesoccurinfiber.

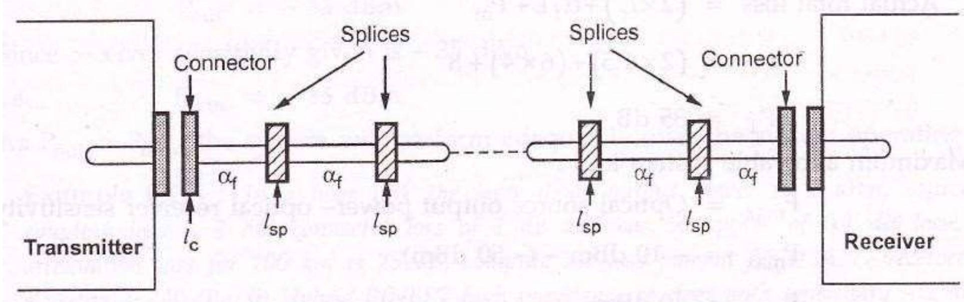


Fig. 6.2.3 Optical power loss model

•Allthelossesfromsourcetodetectorcomprisesthetotalloss(PT)inthesystem.

•Link power margin considers the losses due to component aging and temperature fluctuations. Usuallya link margin of 6-8 dB is considered whileestimatinglink power budget. Total optical loss = Connector loss + (Splicing loss + Fiber attenuation) + System margin (Pm)

PT=2lc+αfL+ Systemmargin (Pm)

Where,

Listransmissiondistance.

Example: Design asoptical fiber link fortransmitting 15 Mb/sec ofdatafora distanceof 4 km with BER of 10^{-9}.

Solution:

BandwidthxLength=15Mb/secx4km=(60Mb/sec)km

Selectingopticalsource:LEDat820nmissuitableforshortdistances.TheLEDgenerates– 10 dBmopticalpowers.

Selecting optical detector: PIN-FER optical detector is reliable and has – 50 dBm sensitivity.

Selectionopticalfiber: Step-indexmultimodefiberisselected.Thefiberhasbandwidthlength product of 100 (Mb/s) km.

Linkspowerbudget:

Assuming:

Splicinglossl_s=0.5dB/slice

Connector loss l_c= 1.5 dB

SystemlinkpowermarginPm–8dB

Fiber attenuation αf = 6 dB/km

Actual total loss = (2 x lc) + αfL + Pm

PT = (2 x 1.5) + (6 x 4) + 8

PT=35 dB

Maximumallowablesystemloss:

P_{max}=Opticalsourceoutputpower-opticalreceiversensitivityP_{max}=-10dBm –(-50dBm) P_{max}= 40

dBm

Sinceactuallossesinthesystemarelessthantheallowableloss,hencethesystemis functional.

Example: A transmitter has an output power of 0.1 mW. It is used with a fiber having NA= 0.25, attenuation of 6 dB/km and length 0.5 km. The link contains two connectors of2 dB average loss. The receiver has a minimum acceptable power (sensitivity) of – 35 dBm. The designer has allowed a 4 dB margin. Calculate the link power budget.

Solution:

SourcepowerPs=0.1mW

P_s= -10dBm

Since NA=0.25

Couplingloss=-10log(NA^2)

=-10log(0.25^2)

=12dB

Fiberloss=α_fxL

l_f=(6dB/km)(0.5km)l_f=3dB Connector

loss = 2 (2 dB)

l_c=4 dBDesignmarginP_m=4 dB

ActualoutputpowerPout=Sourcepower–(ΣLosses)P_{out}=10dBm –[12dB+3+4+4]

P_{out}=**-33dBm**

Sincereceiversensitivitygivenis–35dBm.

P_{min}=**-35dBm**

AsP_{out}>P_{min},thesystemwillperformadequatelyoverthesystemoperatinglife.

Example: In a fiber link the laser diode output power is 5 dBm, source-fiber coupling loss= 3 dB, connector loss of 2 dB and has 50 splices of 0.1 dB loss. Fiber attenuation loss for 100 km is 25 dB, compute the loss margin for i) APD receiver with sensitivity – 40 dBm ii) Hybrid PINFET highimpedance receiver with sensitivity -32 dBm.

Solution:Powerbudgetcalculations

Sourceoutputpower	**5dBm**
Sourcefibercouplingloss	**3dB**
Connectorloss	**2dB**
Connectorloss	**5dB**
Fiber attenuation	**25dB**
Totalloss	**35dB**

Availablepowertoreceiver:(5dBm–35dBm)–30dBm

APDreceiversensitivity–40dBm

Lossmargin[-40 –(-30)]10dBm

H-PINFET high0impedancereceiver-32dBmLossmargin[-32– (-30)]2dBm

RiseTime Budget

Risetimegivesimportantinformationforinitialsystemdesign.Rise-timebudgetanalysis determines the dispersion limitation of an optical fiber link.

Totalrisetimeofafiberlinkistheroot-sum-squareofrisetimeofeachcontributortothe pulse rise time degradation.

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

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

The link components must be switched fast enough and the fiber dispersion must be low enoughtomeetthebandwidthrequirementsoftheapplicationadequatebandwidthfora system can be assured by developing a rise time budget.

As the light sources anddetectors has a finite response time to inputs. The device does not turn-onorturn-offinstantaneously.Risetimeandfalltimedeterminestheoverallresponse time and hence the resulting bandwidth.

Connectors,couplersandsplicesdonotaffectsystemspeed,theyneednotbeaccountedin rise time budget but they appear in the link power budget. Four basic elements that contributes to the rise-time are,

Transmitterrise-time(ttx)

GroupVelocityDispersion(GVD)risetime(tGVD)Modaldispersionrisetimeoffiber(tmod)

Receiver risetime(trx)

Where,

B_{rx}is3 dB– bWof receiver (MHz).

Risetimeduetomodaldispersionisgivenas

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

where,

$B_M$isbandwidth(MHz)

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

Lislengthoffiber(km)

qIsaparameterrangingbetween0.5and1. $B_0$is

bandwidth of 1 km length fiber

- Risetimeduetogroupvelocitydispersionis

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

Where,

Disdispersion [ns/(nm.km)]

$\Sigma_\lambda$ishalf-powerspectralwidthofsourceLislengthof fiber

•Receiverfrontendrise-timeinnanosecondsis

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

Equation(6.2.1)canbewritten as

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

$$t_{sys} = \left[t_{tx}^2 + \left(\frac{440\ Lq}{B_0}\right)^2 + D^2\sigma_\lambda^2 L^2 + \left(\frac{350}{B_{rx}}\right)\ \right]^{1/2}$$

Example:Foramultimodefiberfollowingparametersarerecorded.

LEDwithdrivecircuithasrisetimeof15ns. LED

spectral width = 40 nm

Materialdispersionrelatedrisetimedegradation =21nsover6kmlink.

Receiver bandwidth = 235 MHz

Modaldispersionrisetime=3.9nsec

Calculatesystemrisetime.

Solution : t_{tx}=15nsectT_{mat}=21nsect$_{mod}$=3.9nsec Now

$$t_{rx} = \frac{350}{25} \qquad t_{rx} = \frac{350}{B_{rx}}$$

$$t_{rx} = 14 \text{ nsec}$$

Since

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

$$t_{sys} = [15^2 + 21^2 + 3.9^2 + 14^2]^{1/2}$$

$$t_{sys} = 29.61 \textbf{ nsec}$$

Example:Afiberlinkhasfollowing data

Component	BW	Risetime(tr)
Transmitter	200MHxz	1.75nsec
LED(850 nm)	100MHz	3.50nsec
Fiber cable	90MHz	3.89nsec
PINdetector	350 MHz	1.00nsec
Receiver	180 MHz	1.94nsec

Computethesystemrisetimeandbandwidth.Solution: System

rise time is given by

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

$$ct_{sys} = \sqrt{(1.75^2 + 3.5^2 + 3.89^2 + 1.00^2 + 1.94^2)}$$

$$t_{sys} = \mathbf{5.93\ nsec}$$

SystemBWisgivenby

$$BW = \frac{0.35}{5.93\ nsec}$$

$$BW = \frac{0.35}{t_{sys}}$$

WDM

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

NEED OFWDM

Due to the rapid growth in telecommunication links, high capacity and faster data transmission rates over farther distances are required. To meet these demands, network managers are relying more and more on fiber optics. Typically, there are three methods for expanding capacity: installing more cables, increasing system bitrate to multiplex more signals and wavelength division multiplexing.

The first method, installing more cables, will be preferred in many cases, especially in metropolitan areas, since fiber has become incredibly inexpensive and installation methods more efficient. Butwhen conduit space isnot availableor major construction isnecessary, this maynot be the most cost-effective.

Another way for capacity expansion is to increase system bitrate to multiplex more signals. But increasing system bitrate may not prove cost effective either. Since many systems are already running at SONET OC-48 rates (2.5 GB/s) and upgrading to OC-192 (10 GB/s) is expensive,requires changing out all the electronics in a network, and adds 4 times the capacity, may not be necessary.

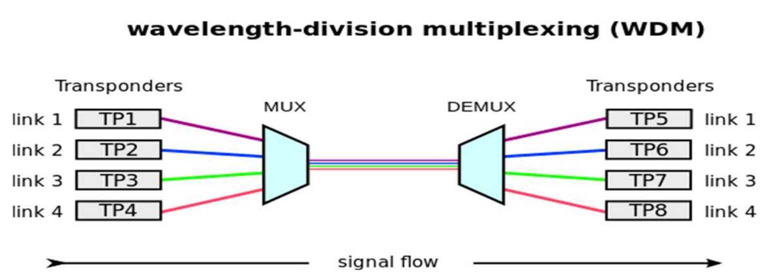
Thirdly, the WDM has been proved to be the more cost-effective technology. It does not only support current electronics and fibers but also can share fibers by transmitting channels at different wavelengths (colors) of light. Besides, systems are alreadyusingfiber optic amplifiers as repeaters also do not require upgrading for most WDM.

From the above comparison of three methods for expanding capacity, we can easily draw a conclusion that WDM is the best solution to meet the demand for more capacity and faster data transmission rates.

Actually, it is not difficult to understand the operating principle of WDM. Consider the fact that you can see many different colors of light: red, green, yellow, blue, etc. The colors aretransmitted through the air together and may mix, but they can be easily separated by using a simple device like a prism.

It's like we separate the "white" light from the sun into a spectrum of colors with the prism.WDM is equivalent to the prism in the operating principle. A WDM system uses a multiplexer at the transmitter to joint the several signals together. At the same time, it uses a demultiplexer at the receiver to splitthem apart, as shown inthefollowing diagram. Withthe righttype of fiber, it is possible to function as an optical add-drop multiplexer.

This technique was originally demonstrated with optical fiber in the early 80s. The first WDM systems combined only two signals. Modern systems can handle up to 160 signals and can thus expand a basic 10 Gbit/s system over a single fiber pair to over 1.6 Tbit/s. Because WDM systems can expand the capacity of the network and accommodate several generations of technology developmentinopticalinfrastructurewithouthavingtooverhaulthebackbonenetwork,theyare popular with telecommunications companies.



CWDMVSDWDM

WDMsystemsaredividedintodifferentwavelengthpatterns:CWDM(CoarseWavelength Division Multiplexing) and DWDM (Dense Wavelength Division Multiplexing). There are many differences between CWDM and DWDM: spacings, DFB lasers, and transmission distances.

The channel spacingsbetween individual wavelengthstransmitted through the same fiber serve as the basis for defining CWDM and DWDM. Typically, the spacing in CWDM systems is 20 nm, while most DWDM systems today offer 0.8 nm (100 GHz) wavelength separation accordingto the ITU standard.

Due to wider CWDM channel spacing, the number of channels (lambdas) available on the same link is significantly reduced, but the optical interface components do not have to be as precise as DWDM components. CWDM equipment is thus significantly cheaper than DWDM equipment.

Both CWDM and DWDM architectures utilize the DFB (Distributed Feedback Lasers). However, CWDM systems use DFB lasers that are not cooled. These systems typically operate from0to70°Cwiththelaserwavelengthdriftingabout6nmoverthisrange.Coupledwith thelaser wavelength of up to ±3 nm, the wavelength drift yields a total wavelength variation of about ±12 nm.

DWDM systems, on the other hand, require the larger cooled DFB lasers, because a semiconductorlaserwavelengthdrifts about0.08nm/°Cwithtemperature. DFB lasersarecooled to stabilize the wavelength from outside the passband of the multiplexer and demultiplexerfilters as the temperature fluctuates in DWDM systems.

Due to the unique attributes of CWDM and DWDM, they are deployed for different transmission distances. Typically, CWDM can travel anywhere up to about 160 km. If we need to transmit the data over a long range, the DWDM system is the best choice. DWDM supports1550 nm wavelength size, which can be amplified to extend transmission distance to hundreds of kilometers.

OPERATIONALPRINCIPLESOF WDM

Since the spectral width of a high-quality source occupies only a narrow slice of optical bandwidth,thereare manyindependentoperatingregionsacrossthespectrum,rangingfromthe a-band through the L-band, that can be used simultaneously.The original use of WDM was to upgrade the capacity of installed point-to-point transmission links.

This was achieved with wavelengths that were separated from several tens up to 200 nm in order not to impose strict wavelength-tolerance requirements on the different laser sources and the receiving wavelength splitters. Subsequently, the development of lasers that have extremely narrow spectraJemission widths allowed wavelengths to be spaced less than a nanometerapart.Thisisthebasisofwavelength-divisionmultiplexing,whichsimultaneouslyuses a number of light sources, each emitting at a slightly different peak wavelength.

Each wavelength carries an independent signal, so that the link capacity is increased greatly. The main trick is to ensure that the peak wavelength of a source is spaced sufficiently far from its neighbor so as not to create interference between their spectral extents.Equally important is the requirement that during the operation of a system these peak wavelengths do not drift into the spectral territory occupied by adjacent channels. In addition to maintaining strict control of the wavelength, system designers include an empty guardband between the channels as an operations safety factor.

Thereby the fidelities of the independent messages from each source are maintained for subsequent conversion to electrical signals at the receiving end.

WDMOperatingRegions

The possibility of having an extremely high-capacity link by means of WDM can be seen by examining the characteristics of a high-quality optical source. As an example, a distributed-feedback (DFB) laser has a frequency spectrum on the order of I MHz, which is equivalent to a spectral linewidth of 10-5 nm. With such spectralwidths, simplex systemsmake use of only atiny portion of the transmission bandwidth capability of a fiber. This can be seen from Figure 3.1, which depicts the attenuation of light in a silica fiber as a function of wavelength. The curve shows that the two low-loss regions of a standard G.652 single-mode fiber extend over the O-bandwavelengthsrangingfromabout1270to1350nm(originallycalledthesecondwindow)and from 1480 to 1600nm (originally called the third window). We can view these regions either in terms of spectral width (the wavelength band occupied by the light signal) or by means of optical bandwidth (the frequency band occupied by the light signal).

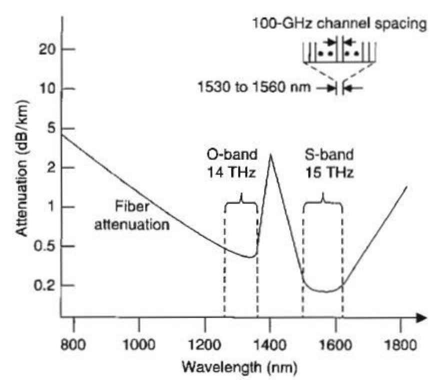


Figure 3.1. Generic representation of the attenuation of light in a silica fiber as a function of wavelength.

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

$$\Delta\nu = \frac{c}{\lambda^2}\Delta\lambda \qquad (3.1)$$

where the frequency deviation $\Delta\nu$ corresponds to the wavelength deviation $\Delta\lambda$ around λ.

Now suppose we have a fiber that has the attenuation characteristic shown in Figure 3.1. From Eq. (3.1) the optical bandwidth is .Deltav= 14THz for a usable spectral band .DeltaLamda= 80 nm in the center of the O-band. Similarly, .Deltav= 15 THz for a usable spectral band DeltaLamda=120 nmin the low-lossregion runningfromnearthebeginningof the S-band to almosttheendof the L-band. This yields a total available fiber bandwidth of about 30THz in the two low-loss windows.

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

GenericWDMLink

The implementation of WDM networks requires a variety of passive and/or active devices to combine, distribute, isolate, add, drop, attenuate, and amplify optical power at different wavelengths. Passive devices require no external electric power or control for their operation, so they have a fixed application in WDM networks. These passive components are used to separate and combine wavelength channels, to divide optical power onto a number of fiber lines, or to tap off part of an optical signal for monitoring purposes.

The performance of active devices can be controlled electronically, thereby providing a large degree of network flexibility, Active WDM components include tunable optical filters, tunable lightsources,configurableadd/dropmultiplexers,dynamicgainequalizers,andopticalamplifiers.

Figure 3.2 shows the implementation of a simple WDM link. The transmitting side has a series of independently modulated fixed-wavelength light sources, each of which emits signals at a unique wavelength. Here a multiplexer (popularly called a mux) is needed to combine these optical outputs into a continuous spectrum of signals and couple them onto a single fiber. Within a standard telecommunication link there may be various types of optical amplifiers, a variety of specialized active components (not shown), and passive optical power splitters. The operations and maintenance benefits of PONs are that no active devices are used between the transmitting and receiving endpoints.

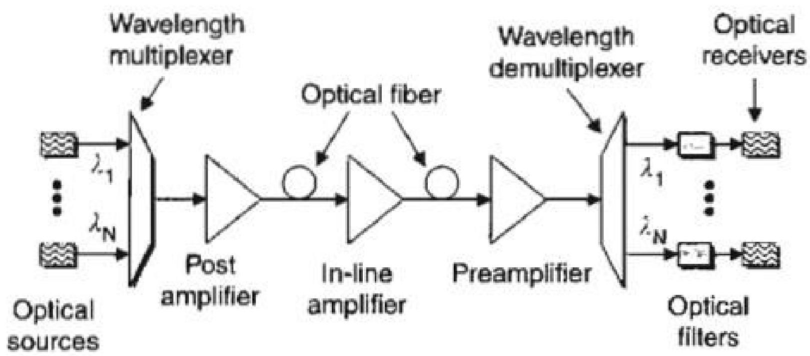


Figure 3.2. Implementation of a simple WDM link.

At the receiving end a demultiplexer is required to separate the individual wavelengths of the independent optical signals into appropriate detection channels for signal processing. At the transmitter the basic design challenge is to have the multiplexer provide a low-loss path from each optical source to the multiplexer output. A different requirement exists for the demultiplexer, since photodetectors usually are sensitive over a broad range of wavelengths, which could include all the WDM channels.

To prevent spurious signals from entering a receiving channel, that is, to give good channel isolation of the differentwavelengthsbeingused, the demultiplexer must exhibit narrow spectral operation or very stable optical filters with sharp wavelength cutoffs must be used.

The tolerable crosstalk levels between channels can vary widely depending on the application. In general,a -lOdBlevelisnot sufficient,whereasalevelof -30dBisacceptable.In principle, any optical demultiplexer can also be used as a multiplexer. For simplicity, the word multiplexer is used as a general term to refer to both combining and separating functions, except when it is necessary to distinguish the two devices or functions.

WavelengthDivisionMultiplexing(WDM)

• Optical signals of different wavelength (1300-1600 nm) can propagate without interfering with each other. The scheme of combining a number of wavelengths over a single fiber is called wavelength division multiplexing (WDM).

• Each input is generated by a separate optical source with a unique wavelength. An optical multiplexer couples light from individual sources to the transmitting fiber. At the receiving station, an optical demultiplexer is required to separate the different carriers before photodetection of individual signals. Fig. 7.1.1 shows simple SDM scheme.

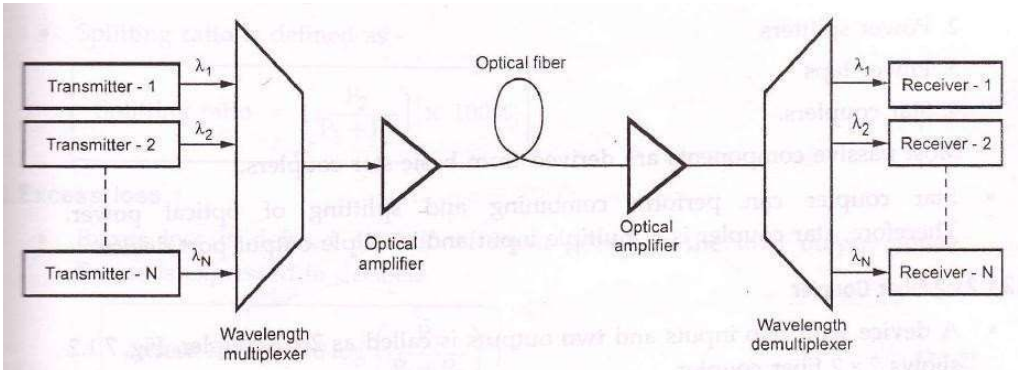


Fig. 7.1.1 WDM scheme

- Topreventspurioussignalstoenterintoreceivingchannel,thedemultiplexermusthave narrow spectral operation with sharp wavelength cut-offs. The acceptable limit of crosstalk is – 30 dB.

FeaturesofWDM

- ImportantadvantagesorfeaturesofWDMareasmentionedbelow–
- Capacityupgrade:SinceeachwavelengthsupportsindependentdatarateinGbps.
- Transparency:WDMcancarryfastasynchronous,slowsynchronous,synchronousanalogand digitaldata.
- Wavelengthrouting:Linkcapacityandflexibilitycanbeincreasedbyusingmultiplewavelength.
- Wavelengthswitching:WDMcanaddordropmultiplexers,crossconnectsandwavelength converters.

PassiveComponents

ForimplementingWDMvariouspassiveandactivecomponentsarerequiredtocombine,distribute, isolate and to amplify optical power at different wavelength.

Passive components are mainly used to split or combine optical signals. These components operates in optical domains. Passive components don't need external control for their operation. Passive components are fabricated by using optical fibers by planar optical waveguides. Commonly required passive components are –

- Nx Ncouplers
- Powersplitters
- Power taps
- Starcouplers.

Mostpassivecomponentsarederivedfrombasicstatcouplers.

Statcouplercanpersoncombiningandsplittingofopticalpower.Therefore,starcouplerisamultiple input and multiple output port device.

Dense Wavelength Division Multiplexing (DWDM)

DWDM:

- DWDM(Densewavelength–divisionmultiplexing)isadatatransmissiontechnology having very large capacity and efficiency.
- Multipledatachannelsofopticalsignalsareassigneddifferentwavelengths,andare multiplexed onto one fiber.
- DWDMsystemconsistoftransmitters,multiplexers,opticalampliferanddemultiplexer. Fig. 7.2.1 shows typical application of DWDM system.

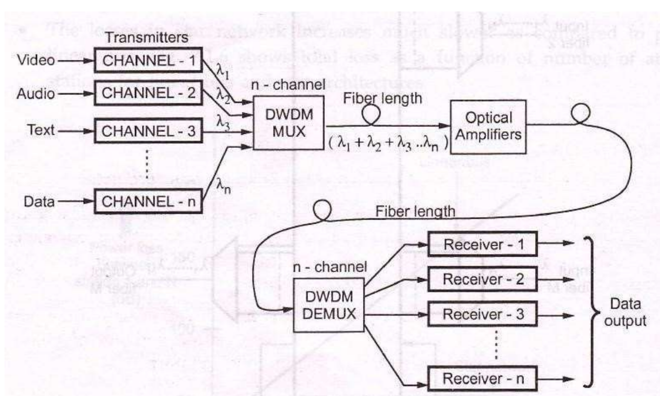


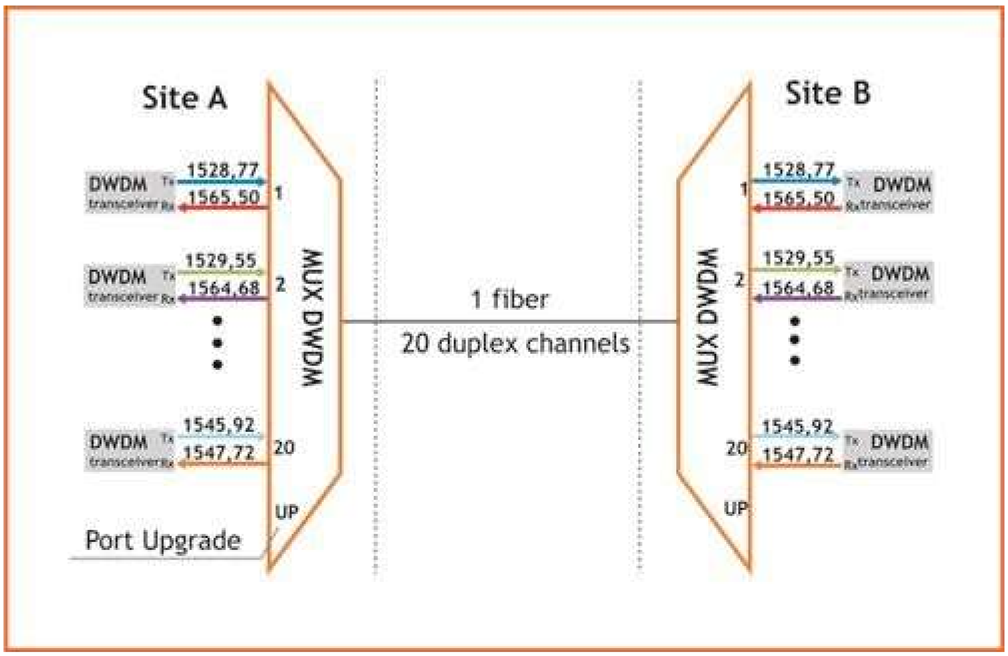
Fig. 7.2.1 DWDM system

- DWDMusedsinglemodefibertocarrymultiplelightwavesofdifferentfrequencies.
- DWDMsystemusesErbium–DopedFiberAmplifers(EDFA)foritslonghaulapplications, andtoovercometheeffectsofdispersionandattenuationchannelspacingof100GHzis used.

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

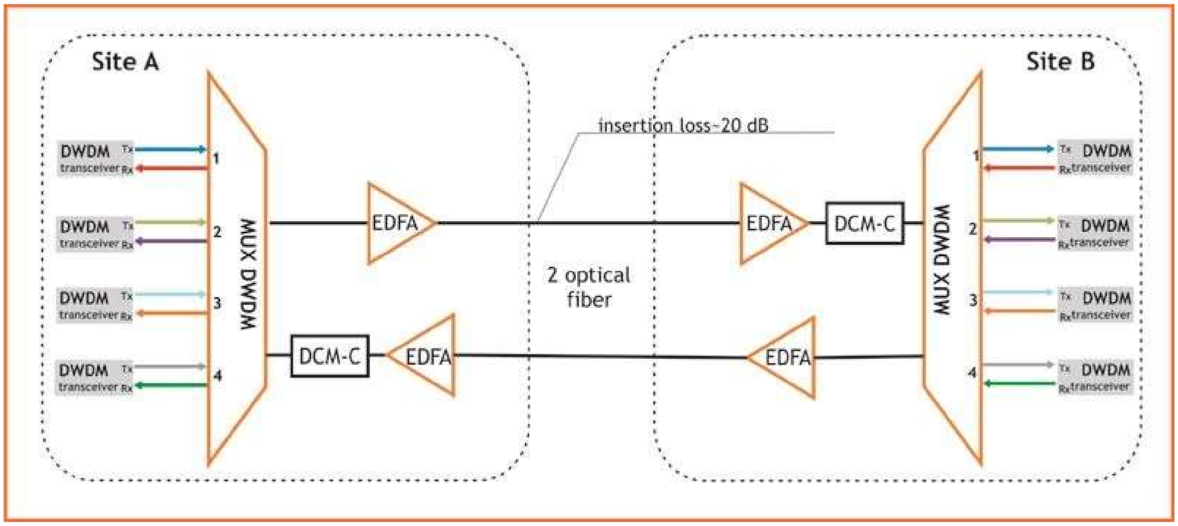
PassiveDWDM

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



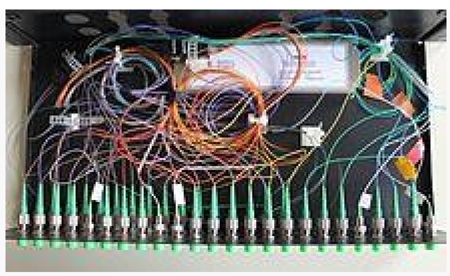
ActiveDWDM

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



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

Atthisstage,abasicDWDMsystemcontainsseveralmaincomponents:



WDMmultiplexerforDWDM communications

1. A DWDM**terminal multiplexer**. The terminal multiplexer contains a wavelength-converting transponder for each data signal, an optical multiplexer and where necessary an optical amplifier (EDFA). Each wavelength-converting transponder receives an optical data signal from the client-layer, such as Synchronous optical networking [SONET /SDH]or another type of data signal, converts this signal into the electrical domain and re-transmits the signal at a specific wavelength using a 1,550 nm band laser. These data signals arethencombined togetherintoa multi-wavelengthoptical signal usinganoptical multiplexer, for transmission over a single fiber (e.g., SMF-28 fiber). The terminal multiplexer may or may not also include a local transmit EDFA for power amplification of the multi-wavelength optical signal. In the mid-1990s DWDM systems contained 4 or 8 wavelength-converting transponders; by 2000 or so, commercial systems capable of carrying 128 signals were available.

2. An **intermediate line repeater** is placed approximately every 80–100km to compensate for the loss of optical power as the signal travels along the fiber. The 'multi-wavelength optical signal' is amplified by an EDFA, which usually consists of several amplifier stages.
3. An **intermediate optical terminal**, or**optical add-drop multiplexer**. This is a remote amplification site that amplifies the multi-wavelength signal that may have traversed up to 140km or morebefore reaching the remote site. Opticaldiagnosticsand telemetryare often extracted or inserted at such a site, to allow for localization of any fiber breaks or signal impairments. In more sophisticated systems (which are no longer point-to-point), several signals out of the multi-wavelength optical signal may be removed and dropped locally.
4. A DWDM **terminal demultiplexer**. At the remote site, the terminal de-multiplexer consisting of an optical de-multiplexer and one or more wavelength-converting transponders separates the multi-wavelength optical signal back into individual data signalsandoutputsthemonseparatefibersforclient-layersystems(suchasSONET/SDH). Originally, this de-multiplexing was performed entirely passively, except for some telemetry, as most SONET systems can receive 1,550 nm signals. However, in order to allow for transmission to remote client-layer systems (and to allow for digital domain signal integrity determination) such de-multiplexed signals are usually sent to O/E/O outputtransponders priortobeing relayed totheir client-layer systems. Often,the functionality of output transponder has been integrated into that of input transponder,so that most commercial systems have transponders that support bi-directionalinterfacesonboththeir1,550 nm(i.e., internal)side,andexternal (i.e., client-facing)side. Transpondersinsomesystemssupporting40 GHznominaloperationmayalso performforwarderrorcorrection (FEC)viadigitalwrappertechnology,asdescribedin the ITU-T G.709 standard.
5. **Optical Supervisory Channel (OSC)**. This is data channel which uses an additional wavelengthusuallyoutsidetheEDFAamplificationband(at1,510 nm,1,620nm, 1,310nm or another proprietary wavelength). The OSC carries information about the multi-wavelength optical signal as well as remote conditions at the optical terminal or EDFA site. It is also normally used for remote software upgrades and user (i.e., network operator) Network Management information. It is the multi-wavelength analogue to SONET's DCC (or supervisory channel). ITU standards suggest that the OSC should utilize an OC-3 signal structure, though some vendors have opted to use 100 megabit Ethernet or another signal format. Unlike the 1550 nm multi-wavelength signal containing client data, the OSC is always terminated at intermediate amplifier sites, where it receives local information before re-transmission.

Optical Network

An Optical Network is basically a communication network used for the exchange of information through an optical fiber cable between one end to another. It is one of the quickest networks used for data communication.

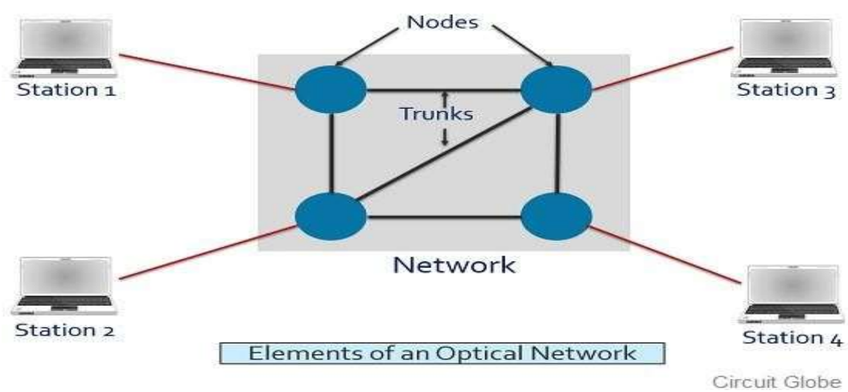
As we already know that data signal through an optical fiber is transmitted in the form of light pulses. So, optical networks are used in order to have optical signal transmission.

Now, the question arises that what is the need for the optical network when we have other communicating networks.

So, the answer to this question basically relies on the ease of transmitting the signal in the formof light pulses. Today's internet era is based on fiber cable and only the optical signals can be transmitted through these cables. Thus, the need for optical network emerges.As we know that transmission through fiber cable is an easier task due to the low production cost of the cable. Along with that, a fiber cable permits large data carrying capacity and longer distance transmission than other cables.Thus, we use fiber cables and hence, the optical network is an important aspect of the communication system.

Elementsofopticalnetwork

Anopticalnetworkisbasicallycomposedofthefollowingelements:



Elements of an Optical Network

Stations: Stations in an optical network serves as the source and destination of the information being transmitted and received. Stations are basically those devices that are used by the users of the network. For example, a computer or any other telecommunication device.

Trunk: A trunk is basically a transmission line i.e., optical fiber cable in order to transmit the optical signal. A network is composed of one or multiple trunks for signal transmission over large distance.

Node: Node is nothing but acts as a hub for multiple transmission lines inside the network. Incase of a single transmission line, an optical network does not require nodes, as in this case stations at both the ends can be directly connected to the fiber cables.

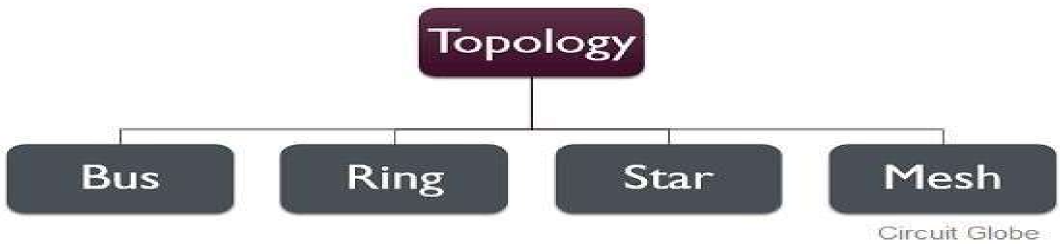
Topology: When multiple fiber cables are employed in an optical network, then these are connected through nodes. But the way in which the multiple nodes are connected together denotes the topology of the network.

Router: A router is basically placed inside an optical network that provides a suitable path for signal transmission.

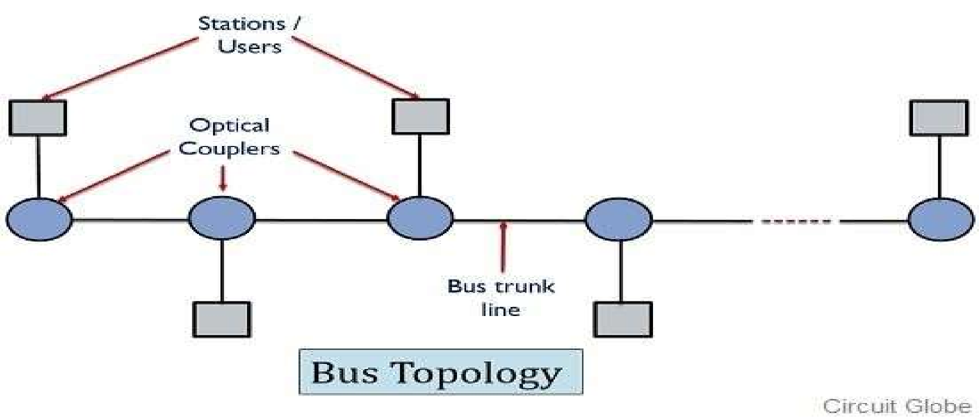
OpticalNetworkTopologies

Aswehavealreadydiscussedinthepreviousssectionthattopologyisthearrangementofmultiple optical fiber transmission lines in an optical network. So, let us now move forward to understand the various topology configurations:

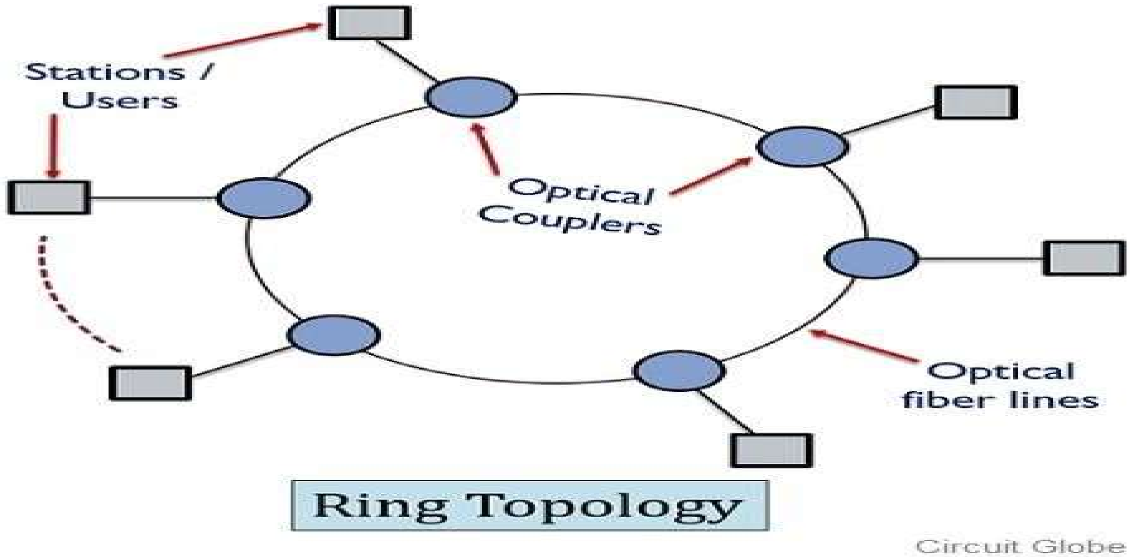
TypesOf Topology



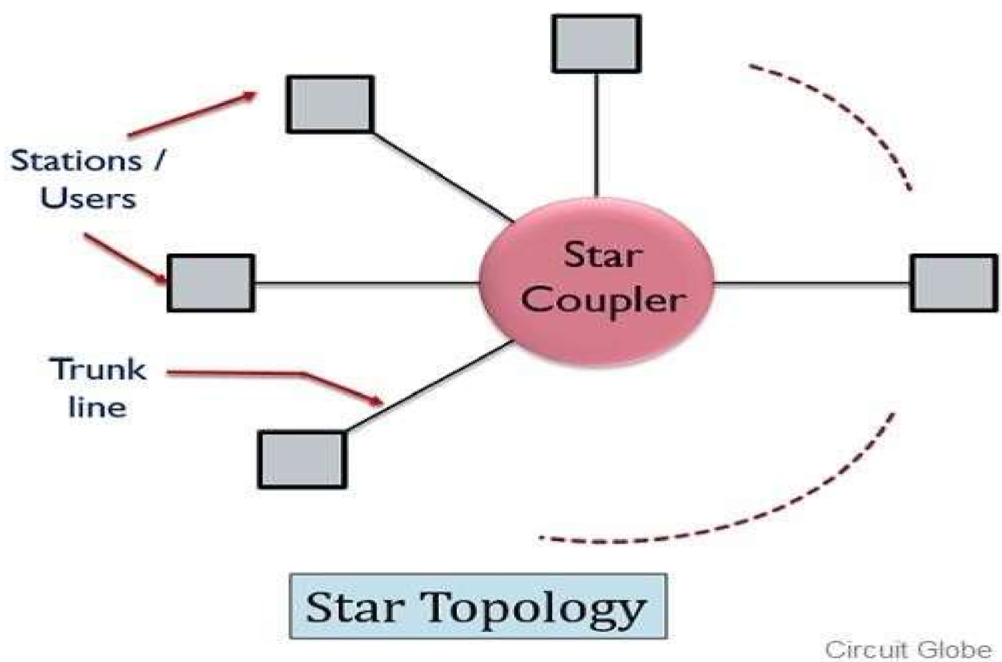
Bus Topology:Inabustopology,thevariousnodesareconnectedthroughasingletrunklinewith the help of optical couplers. This allows a convenient as well as a cost-effective method to transmit the signal. However, in a bus topology, it is difficult to determine the faulted node aswell as it also takes time to restore the transmitted signal from that particular node.



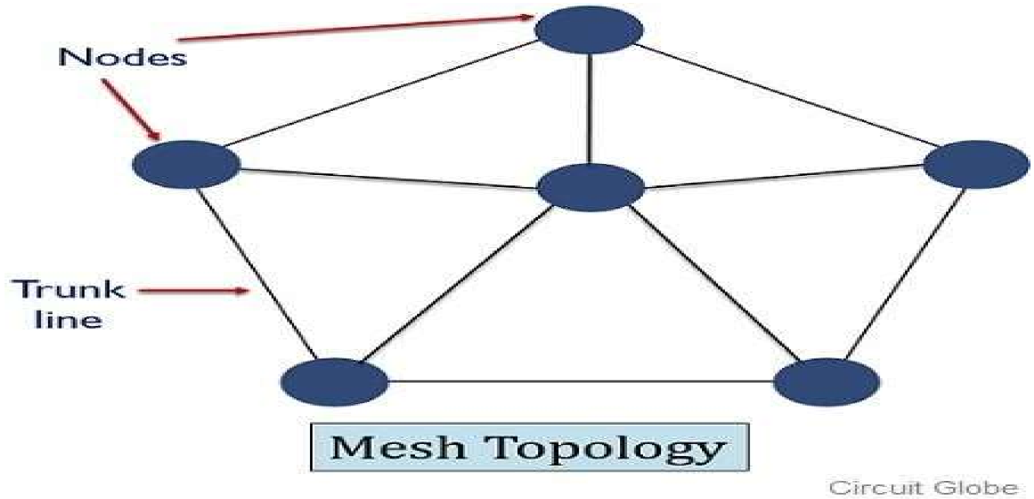
Ring Topology: In a ring topology, one single node is joined to its neighbouring node thereby forming a closed path. So, the transmitted information in the form of light is sent from one node to another. Also, optical couplers are installed within the network in order to the couple the transmitted optical signal from one node to another.



Star Topology: In star connection, the various nodes of the network are connected together with a single central hub. This central hub can be active or passive network. This central hub then controls and directs the transmitted optical signal inside the optical network.



Mesh Topology: In a mesh topology, an arbitrary connection is formed between the nodes in the network. This point to point connection can be changed according to the application. This shows the flexible nature of star topology as in case of failure of one node, others can be used for signal transmission.



Basically, in mesh connection, failure of any link or node is generated then firstly that particular failure is detected and then the signal traffic is diverted from failed node to another link insidethe connection.

CategoriesofOpticalNetwork

The categories of optical network are based on the area that connects the user of the network. These are classified as:

Local Area Network (LAN): Basically a LAN connection provides the interconnection of users that are present in localized areas like a building, a department or an office etc.

The example of networking topology of LAN is Ethernet. As in LAN, users are permitted to share the resources together like servers etc. These are personally owned by an organization. It is quite inexpensive.

Campus network: This network category is formed by the interconnection of multiple LAN's. This is basically extended to alarge level but is stillconfined within a localized area. It is also governed by a single organization.

Theexamplesofcampusnetworkareuniversitycampus,agovernmentorganization,oramedical centre etc.

Metropolitan Area Network (MAN): It is also known as a metro network and covers a greater area than a campus network. It permits the interconnection of several buildings that are present in different cities.

Duetoitslargeoperatingarea,MANiscontrolledbyseveral communication organizations.

Wide Area Network (WAN): Unlike MAN, a WAN provides interconnection of users from neighbouring cities as well as cross-country regions. It is employed to establish communication over a large geographical distance and is controlled and maintained by some privateorganizations or telecommunication service providers.

AdvantagesofOpticalNetwork

Usinganopticalnetworkingsystemishighlyadvantageous.Theadvantagesareasfollows:

- Anopticaltransmissionsystemsupportshighbandwidth.
- Thetransmittedsignalcanbetransmittedtolonger distances.
- Thisnetworkingsystemismoreflexiblethanothertransmissionsystems.

So,wecansayanopticalnetworkprovidesbettersignaltransmissioncapabilitytolongerdistances thus is widely used nowadays.

SynchronousOpticalNetwork(SONET)

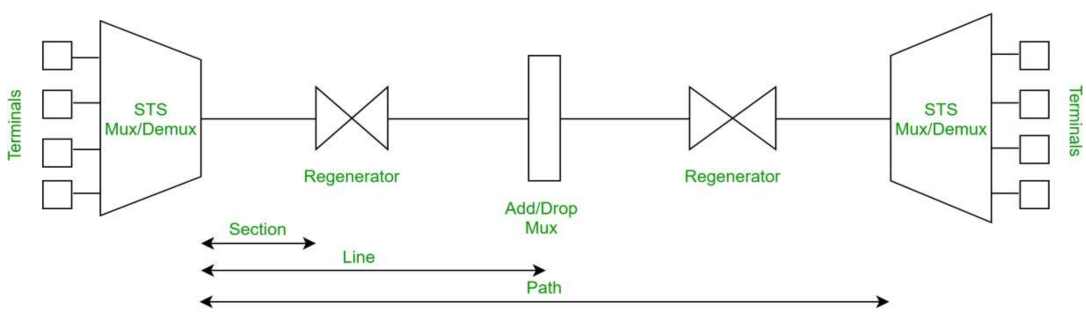
SONET stands for Synchronous Optical Network. SONET is a communication protocol, developed by Bellcore – that is used to transmit a large amount of data over relatively large distances using optical fibre. With SONET, multiple digital data streams are transfered at the same time over the optical fibre.

Key Points:

- DevelopedbyBellcore
- UsedinNorthAmerica
- StandardizedbyANSI(AmericanNationalStandardsInstitute)
- SimilartoSDH(SynchronousDigitalHierarchy)whichisusedinEuropeandJapan.

Asingleclock(Primary Reference Clock,PRC)handles thetimingoftransmissionofsignals& equipments across the entire network.

SONETNetwork Elements:



STS Multiplexer:

- Performsmultiplexingofsignals
- Convertselectricalsignaltoopticalsignal

STS Demultiplexer:

- Performsdemultiplexingofsignals
- Convertsoptical signaltoelectricalsignal

Regenerator:

Itisarepeater,thattakesanopticalsignalandregenerates(increasesthestrength)it.

Add/DropMultiplexer:

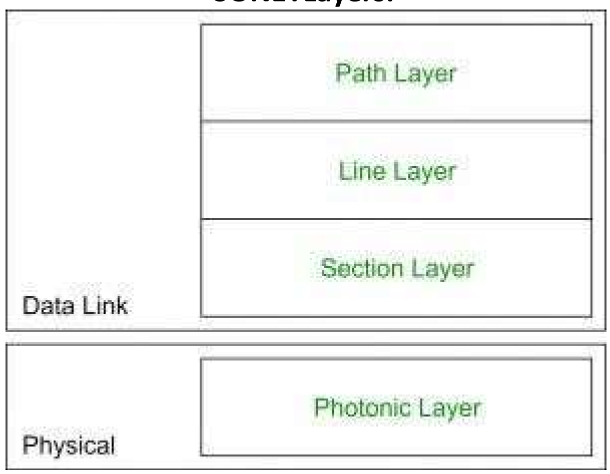
Itallowsaddingsignalscomingfromdifferentsourcesintoagivenpathorremovinga signal.

SONETisusedtoconvertelectricalsignalintoopticalsignalsothatitcantravellongerdistances.

SONETConnections:

- **Section:**Portionofnetworkconnectingtwoneighbouringdevices.
- **Line:**Portionofnetworkconnectingtwoneighbouringmultiplexers.
- **Path:**End-to-endportionofthenetwork.

SONETLayers:



SONETincludesfourfunctionallayers:

1. **Path Layer:**
   - Itisresponsibleforthemovementofsignalfromitsopticalsourcetoitsoptical destination.
   - STSMux/Demuxprovidespathlayerfunctions.
2. **Line Layer:**
   - Itisresponsibleforthemovementofsignalacrossaphysicalline.
   - STSMux/DemuxandAdd/DropMuxprovidesLinelayerfunctions.
3. **SectionLayer:**
   - Itisresponsibleforthemovementofsignalacrossaphysicalsection.
   - Eachdeviceofnetworkprovidessectionlayerfunctions.
4. **Photonic Layer:**
   - ItcorrespondstothephysicallayeroftheOSI model.

1. Itincludesphysicalspecificationsfortheopticalfibrechannel(presenceoflight=1and absence of light = 0).
2. **AdvantagesofSONET:**

- Transmitsdatatolargedistances
- Lowelectromagneticinterference
- Highdata rates
- LargeBandwidth