LECTURE NOTES

ON

OPTICAL COMMUNICATION

Prepared by

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AIM & OBJECTIVES

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

PRE TEST-MCQ TYPE

1. Which equations are best suited for the study of electromagnetic wave propagation?
a) Maxwell’s equations
b) Allen-Cahn equations
c) Avrami equations
d) Boltzmann’s equations

2. When λ is the optical wavelength in vacuum, k is given by k=2Π/λ. What does k stand for in the above equation?
a) Phase propagation constant
b) Dielectric constant
c) Boltzmann’s constant
d) Free-space constant

3. When light is described as an electromagnetic wave, it consists of a periodically varying electric E and magnetic field H which are oriented at an angle?
a) 90 degree to each other
b) Less than 90 degree
c) Greater than 90 degree
d) 180 degree apart

4. Which is the most important velocity in the study of transmission characteristics of optical fiber?
a) Phase velocity
b) Group velocity
c) Normalized velocity
d) Average velocity

UNIT I INTRODUCTION TO OPTICAL FIBERS

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

THEORY

Introduction

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

Optical fiber is used by many telecommunications companies to transmit telephone signals, Internet communication, and cable television signals. Researchers at Bell Labs have reached internet speeds of over 100 peta bit ×kilometer per second using fiber-optic communication. The process of communicating using fiber-optics involves the following basic steps:

1. Creating the optical signal involving the use of a transmitter, usually from an electrical signal

2. Relaying the signal along the fiber, ensuring that the signal does not become too distorted or weak

3. Receiving the optical signal

4. Converting it into an electrical signal

Historical Development

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

In 1880 Alexander Graham Bell and his assistant Charles Sumner Tainter created a very early precursor to fiber-optic communications, the Photophone, at Bell's newly established Volta Laboratory in Washington, D.C. Bell considered it his most important invention. The device allowed for the transmission of sound on a beam of light. On June 3, 1880, Bell conducted the world's first wireless telephone transmission between two buildings, some 213 meters apart. 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 Hopkins and Narinder 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 in 1963. Nishizawa invented the PIN diode and the static induction transistor, both of which contributed to the development of optical fiber communications.

In 1966 Charles K. Kao and George Hockham at STC Laboratories (STL) showed that the losses of 1,000 dB/km in existing glass (compared to 5–10 dB/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 low enough for communication purposes (about 20 dB/km) and at the same time GaAs semiconductor 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.

After a period of research starting from 1975, the first commercial fiber-optic communications system 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 and Pirelli aimed 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) in Turin, 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 fiber was 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 what was then the world's longest commercial fiber optic network, which covered 3,268 km (2,031 mi) and linked 52 communities. By 1987, these systems were operating at bit rates of up to 1.7 Gb/s with repeater spacing up to 50 km (31 mi). The first transatlantic telephone cable to use optical fiber was TAT-8, based on Desurvire optimised 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 arsenide and 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 fibers designed to have minimal dispersion at 1.55 μm or by limiting the laser spectrum to a single longitudinal mode. These developments eventually allowed third-generation systems to operate commercially at 2.5 Gbit/s with repeater spacing in excess of 100 km (62 mi).

The fourth generation of fiber-optic communication systems used optical amplification to reduce the need for repeaters and wavelength-division multiplexing to increase data 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 WDM system can operate. The conventional wavelength window, known as the C band, covers the wavelength range 1.53–1.57 µm, and dry fiber has a low-loss window promising an extension of that range to 1.30–1.65 µm. 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 predicted massive increases in demand for communications bandwidth due to increased use of the Internet, and commercialization of various bandwidth-intensive consumer services, such as video on demand. Internet protocol data traffic was increasing exponentially, at a faster rate than integrated circuit complexity had increased under Moore's Law. From the bust of the dot-com bubble through 2006, however, the main trend in the industry has been consolidation of firms and off shoring of manufacturing to reduce costs.

Advantages of Fiber Optic 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 of interference. 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, which ensures 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 mere 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 can be added to existing cable infrastructure. Because optical cable can provide vastly expanded capacity over the originally laid cable and WDM (wavelength division multiplexing) technology, including CWDM and DWDM, enables fiber cables the ability to accommodate more bandwidth.

Disadvantages of Fiber Optic Transmission

Though fiber optic transmission brings lots of convenience, its disadvantages also cannot be 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 underground.

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 by as 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.

Applications of Optical Fiber Communications

Fiber optic cables find many uses in a wide variety of industries and applications. Some uses of fiber optic cables include:

Medical -Used as light guides, imaging tools and also as lasers for surgeries

Defense/Government-Used as hydrophones for seismic waves and SONAR , as wiring in aircraft, submarines and other vehicles and also for field networking

Data Storage- Used for data transmission

Telecommunications- Fiber is laid and used for transmitting and receiving purposes

Networking- Used to connect users and servers in a variety of network settings and help increase the speed and accuracy of data transmission

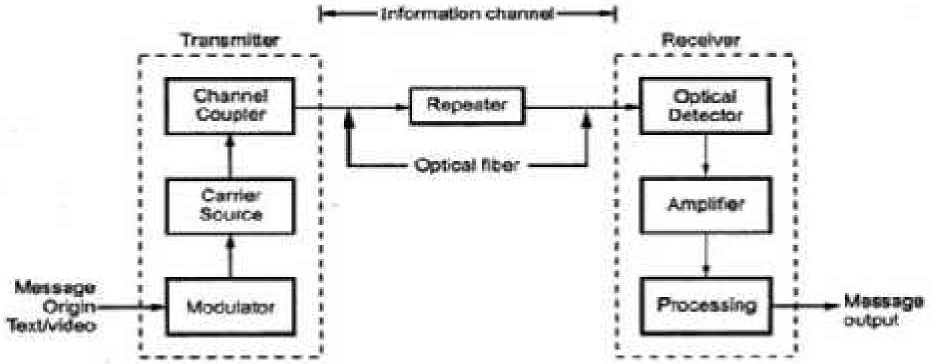
Industrial/Commercial- Used for imaging in hard to reach areas, as wiring where EMI is an issue, as sensory devices to make temperature, pressure and other measurements, and as wiring in automobiles and in industrial settings.

Broadcast/CATV-Broadcast/cable companies are using fiber optic cables for wiring CATV, HDTV, internet, video on- demand and other applications. Fiber optic cables are used for lighting and imaging and as sensors to measure and monitor a vast array of variables. Fiber optic cables are also used in research and development and testing across all the above mentioned industries

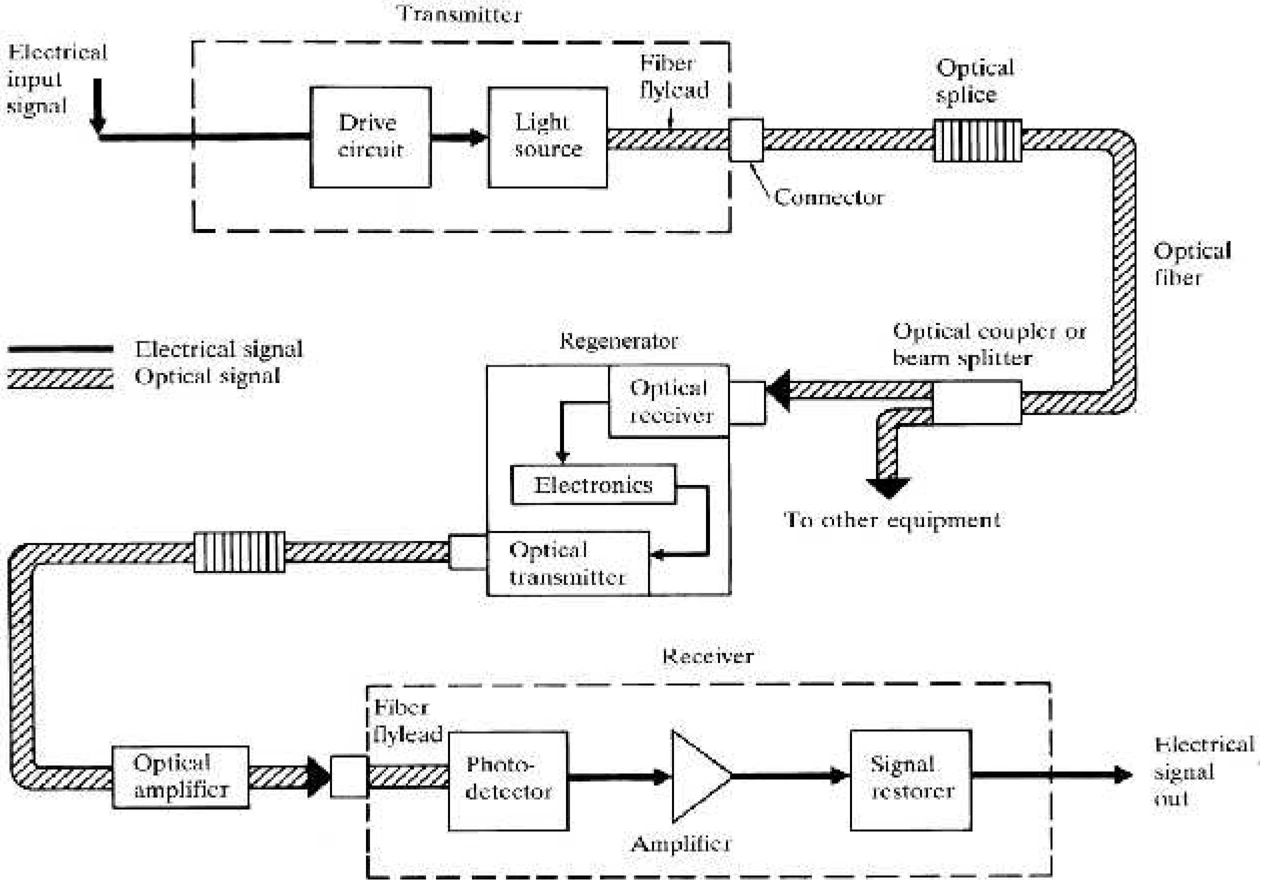
The optical fibers have many applications. Some of them are as follows

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

Block Diagram of Optical Fiber Communication System



Block Diagram of Optical Fiber Communication System



Message origin:

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

Modulator:

The modulator has two main functions.

1) It converts the electrical message into proper format.

2) It impresses this signal onto the wave generated by the carrier source.

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

Carrier source:

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

Channel coupler:

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

Information channel:

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

Another important property of the information channel is the propagation time of the 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.

Optical detector:

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 system decision circuit is an additional block. The bit error rate (BER) should be very small for quality communications.

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Message output:

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

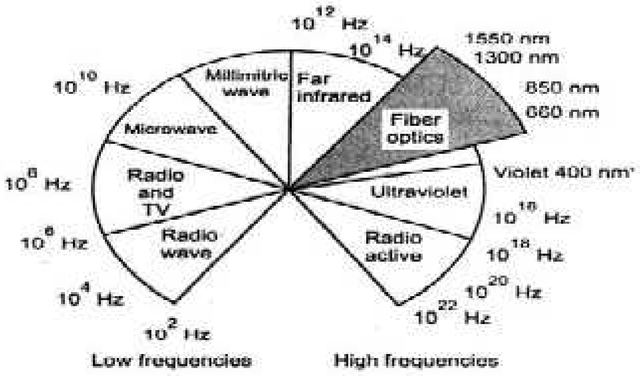
Electromagnetic Spectrum

The radio waves and light are electromagnetic waves. The rate at which they alternate in polarity is called their frequency (f) measured in hertz (Hz). The speed of electromagnetic wave (c) in free space is approximately 3 x 10^8 m/sec. The distance travelled during each cycle is called as wavelength (λ)

In fiber optics, it is more convenient to use the wavelength of light instead of the frequency with light frequencies; wavelength is often stated in microns or nanometers.

1 micron (µ) = 1 Micrometre (1 x 10^{-6}) ;1 nano (n) = 10^{-9} meter

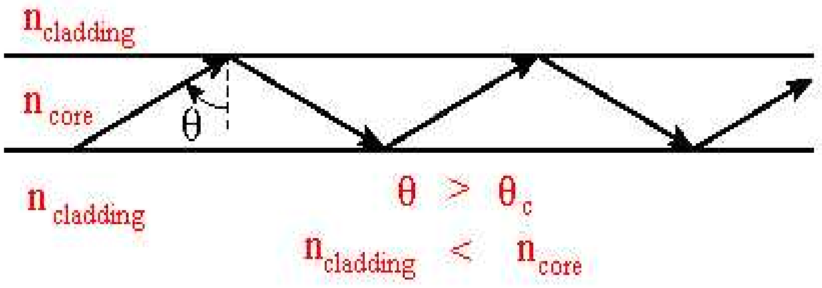
Fiber optics uses visible and infrared light. Infrared light covers a fairly wide range of wavelengths and is generally used for all fiber optic communications. Visible light is normally used for very short range transmission using a plastic fiber



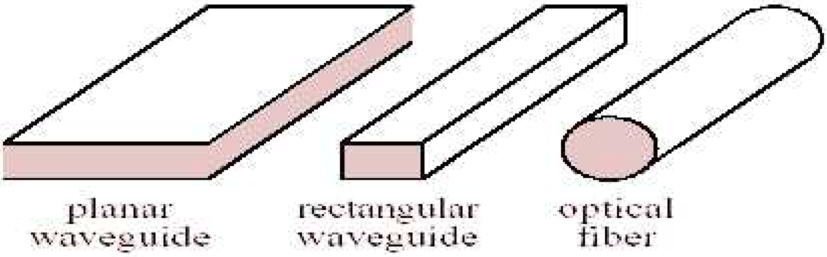
Electromagnetic Spectrum

Optical Fiber Waveguides

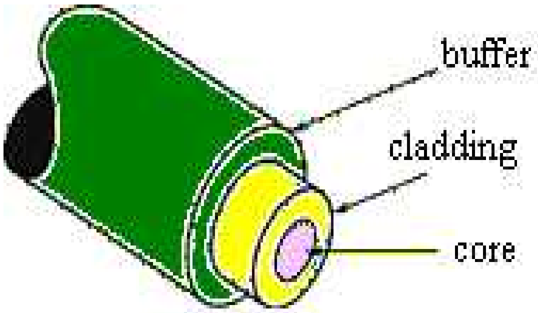
In free space light ravels as its maximum possible speed i.e. 3 x 10^8 m/s or 186 x 10^3 miles/sec. When light travels through a material it exhibits certain behavior explained by laws of reflection, refraction. An optical wave guide is a structure that "guides" a light wave by constraining it to travel along a certain desired path. If the transverse dimensions of the guide are much larger than the wavelength of the guided light, that explain how the optical waveguide works using geometrical optics and total internal reflection.



A wave guide traps light by surrounding a guiding region, called the core, made from a material with index of refraction n_{core}, with a material called the cladding, made from a material with index of refraction $n_{cladding} < n_{core}$. Light entering is trapped as long as $\sin\theta > n_{cladding}/n_{core}$.



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



Fiber Optic Core: the inner light-carrying member with a high index of refraction.

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

Buffer: The outer layer, which serves as a "shock absorber" to protect the core and cladding from damage. The coating usually comprises one or more coats of a plastic material to protect the fiber from the physical environment.

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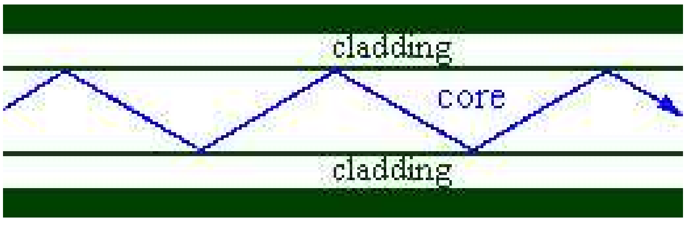
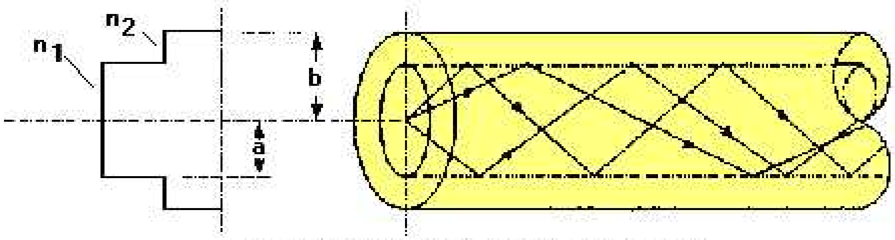


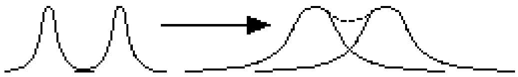
Light injected into the fiber optic core and striking the core-to-cladding interface at an angle greater than the critical angle is reflected back into the core. Since the angles of incidence and reflection are equal, the light ray continues to zigzag down the length of the fiber. The light is trapped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



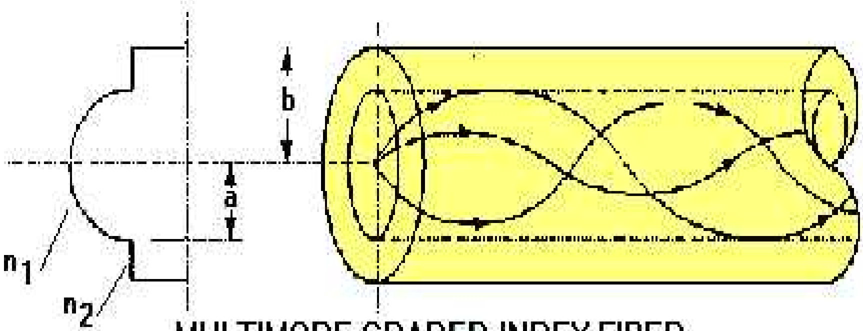
MULTIMODE STEP-INDEX FIBER

Fibers for which the refractive index of the core is a constant and the index changes abruptly at 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 fibers trap light with many different entrance angles, each mode in a step-index multimode fiber is associated with a different entrance angle. Each mode therefore 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. Pulses that enter well separated from each other will eventually overlap each 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.

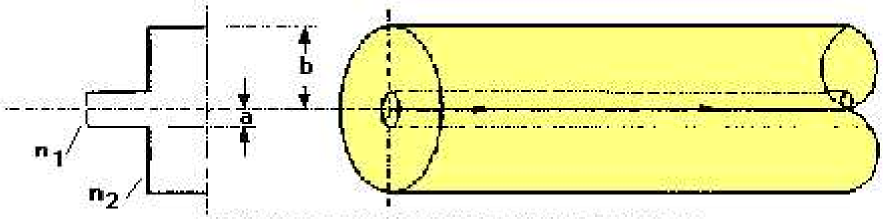


In a multimode graded-index fiber the core has an index of refraction that decreases as the radial distance from the center of the core increases. As a result, the light travels faster near the edge of the core than near the center. Different modes therefore travel in curved paths with nearly equal travel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



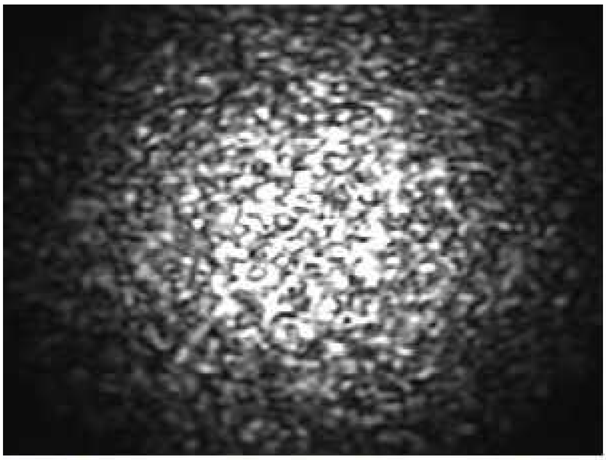
MULTIMODE GRADED-INDEX FIBER

A single mode fiber only allows light to propagate down its center and there are no longer different velocities for different modes. A single mode fiber is much thinner than a multimode fiber and can no longer be analyzed using geometrical optics. Typical core diameters are between 5 mm and 10 mm.

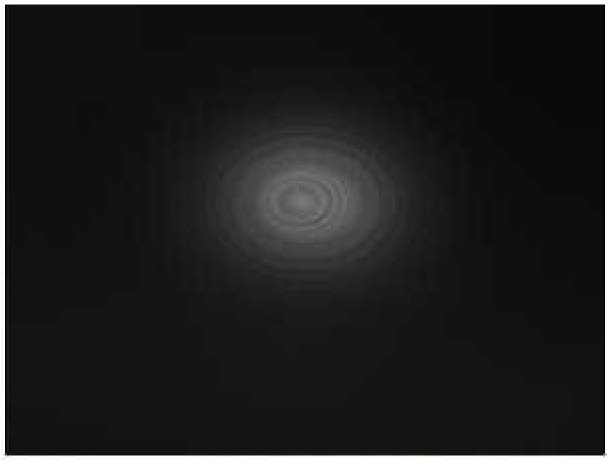


SINGLE MODE STEP-INDEX FIBER

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.



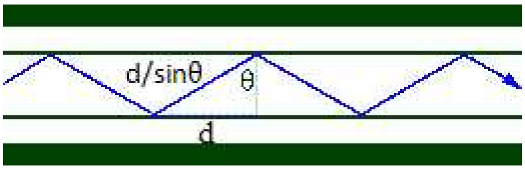
Light emerging from a multi-mode fiber



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 the knees, or other joints in the body

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 by those two rays for a fiber with n_{core} = 1.5 and $n_{cladding}$ = 1.485.



Solution:

If a ray propagating along the axis of the fiber travels a distance d, then a ray incident at the critical angle θ_c travels a distance $L = d/\sin\theta_c$.

The respective travel times are $t_d = d_n\text{core}/c$ and $t_L = d_n\text{core}/(\sin\theta_c\, c)$.

$\sin\theta_C = n\text{cladding}/n\text{core}$.

$\theta_C = 81.9$ deg.

For d = 1000 m , $t_d = 5000$ ns and $t_L = 5050.51$ ns.

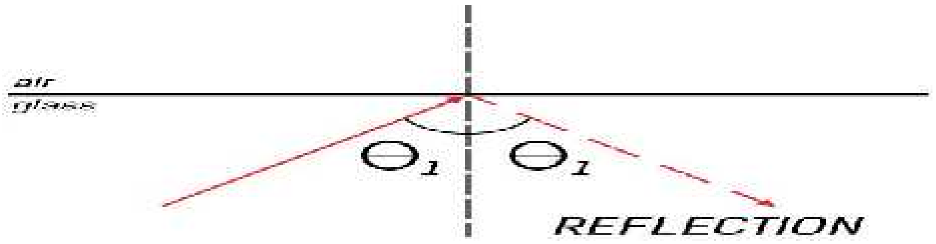
The difference in travel time is therefore 50.51 ns/km.

Ray theory

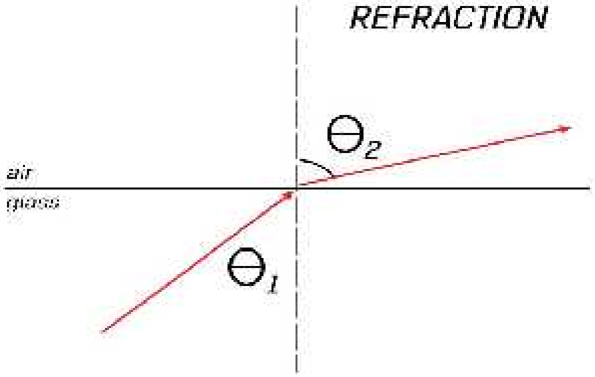
The phenomenon of splitting of white light into its constituents is known as dispersion. The concepts of reflection and refraction of light are based on a theory known as Ray theory or geometric optics, where light waves are considered as waves and represented with simple geometric lines or rays.

The basic laws of ray theory/geometric optics

- In a homogeneous medium, light rays are straight lines.
- Light may be absorbed or reflected.
- 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, has the 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 is the bending of light in a particular medium due to the speed of light in that medium. The speed of light in any medium can be given by

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

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

The refractive index for vacuum and air is 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 media with different refractive indices, it will bend either towards or away from the normal depending on the refractive indices of the media. According to Snell's law, refraction can be represented as

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

n_1 = refractive index of first medium

n_2

θ_1 = angle of incidence, n_2= refractive index of second medium

θ_2 = angle of refraction

For $n_1 > n_2$, θ_2 is always greater than θ_1. Or to put it in different words, light moving from a medium of high refractive index (glass) to a medium of lower refractive index (air) will move away from the normal.

Total internal reflection

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 by their index of refraction, referred to as n. The refractive index of a medium is defined 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.

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

where nI and nR are the indices of refraction of the materials through which the beam is refracted 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 reflected back into the incident medium without loss by a process known as total internal reflection .

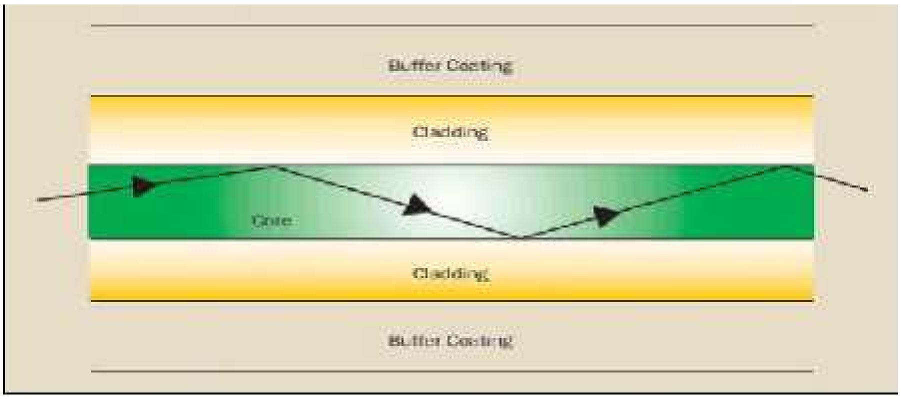


Figure Total Internal Reflection allows light to remain inside the core of the fiber

Refraction is described by Snell's law:

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 . 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 $n1$, then the refraction is such that the ray path in this lower index medium is at an angle to the normal, where is greater than . The angles of incidence and refraction are related to each other and to the refractive indices of the dielectrics by Snell's law of refraction, which states that:

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

Or

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

It may also be observed in Figure 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°.

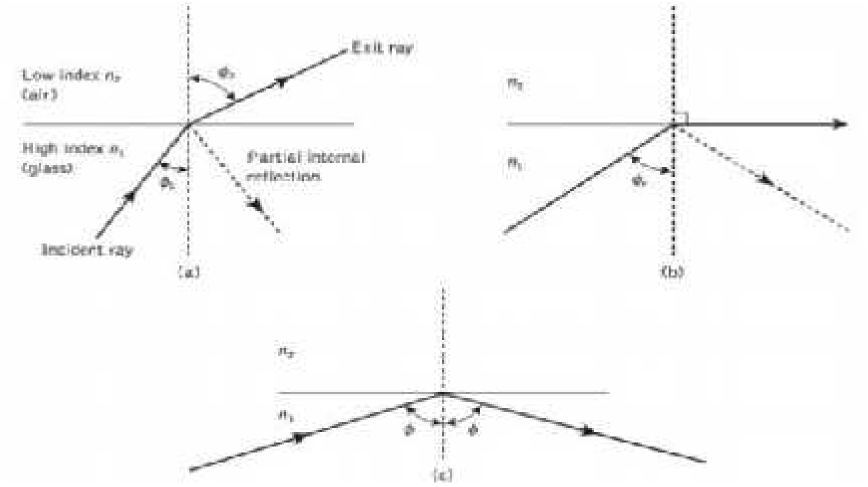


Figure Light rays incident on a high to low refractive index

This is the limiting case of refraction and the angle of incidence is now known as the critical angle φ_c, as shown in Figure. The value of the critical angle is given by

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

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 that total internal reflection occurs at the inter- face between two dielectrics of differing refractive indices when light is incident on the dielectric of lower index from the 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.

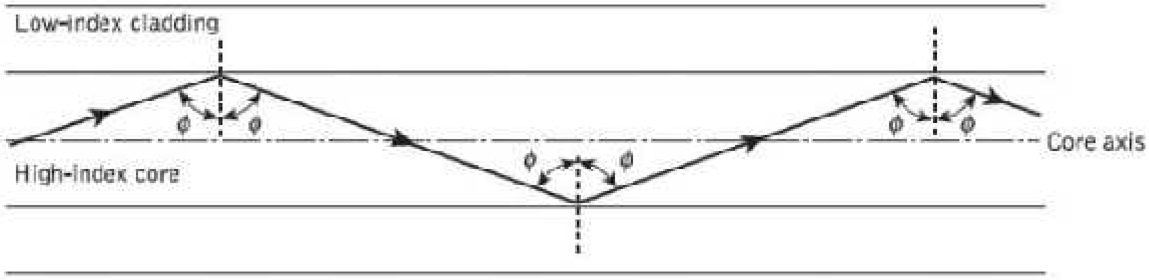


Figure Transmission of a light ray in a perfect optical fiber

The above figure 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 has an angle of incidence φ at the interface which is greater than the critical angle and is reflected at the same angle to the normal. The light ray shown in Figure is known as a meridional ray as it passes through 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 light transmission illustrated in Figure 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.

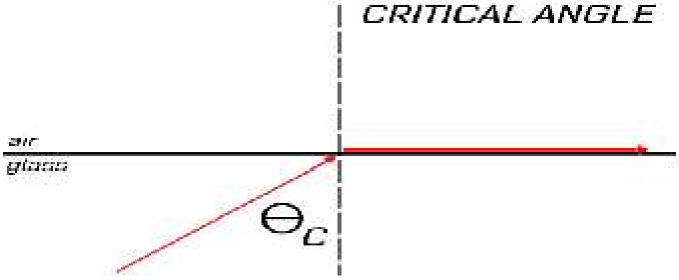
Critical Angle

When the angle of incidence is progressively increased, there will be progressive increase of refractive angle. At some condition the refractive angle becomes 90^{o} to the normal. When this happens the refracted light ray travels along the interface. The angle of incidence at the point at which the refractive angle becomes 90^{o} is called the critical angle. The critical angle is defined as the minimum angle of incidence at which the ray strikes the interface of two media and causes an angle of refraction equal to 90^{o}. Figure 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. Using Snell's law

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

$$\because \qquad \sin 90^0 = 1$$

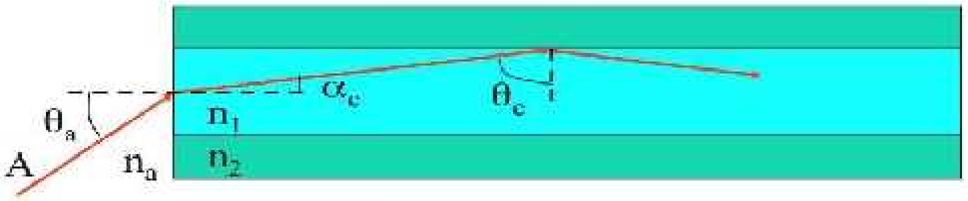
$$\boxed{\text{Critical angle } \phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)}$$



It is important to know about this property because reflection is also possible even if the surfaces are not 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.

Acceptance angle

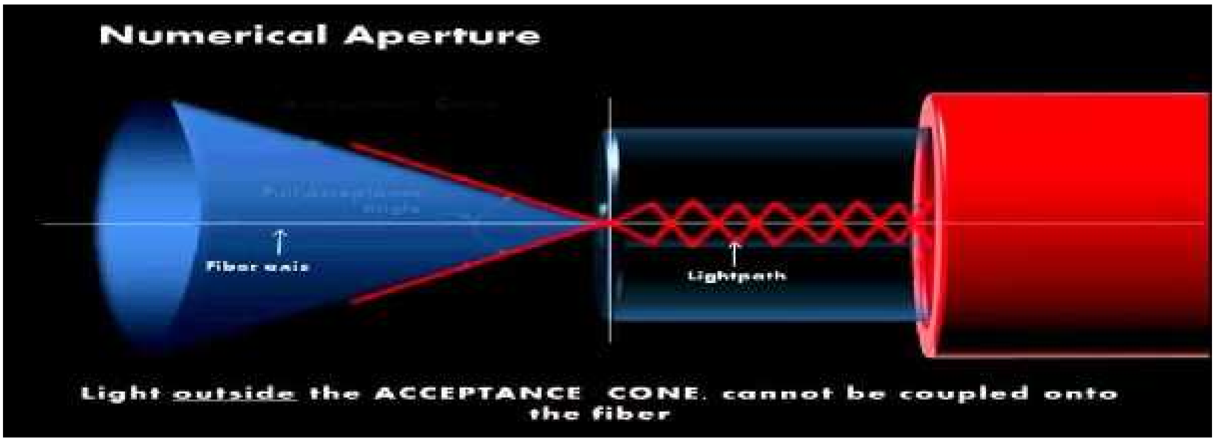
In an optical fiber, a light ray undergoes its first refraction at the air-core interface. The angle at which this refraction occurs is crucial because this particular angle will dictate whether the subsequent internal reflections will follow the principle of Total Internal Reflection. This angle, at which the light ray first encounters the core of an optical fiber is called Acceptance angle.

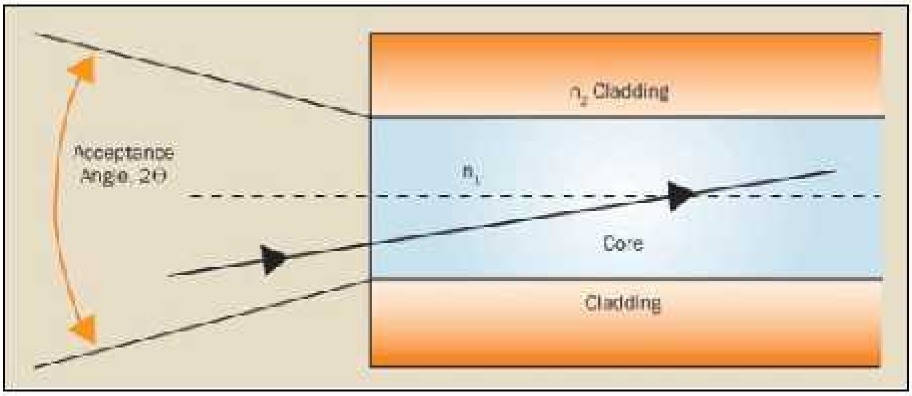


The objective is to have θ_c greater than the critical angle for this particular setting. As you can notice, θ_c depends on the orientation of the refracted ray at the input of the optical fiber. This in turn depends on θ_α, the acceptance angle. The acceptance angle can be calculated with the help of the formula below.

Numerical Aperture

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 the entire 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).

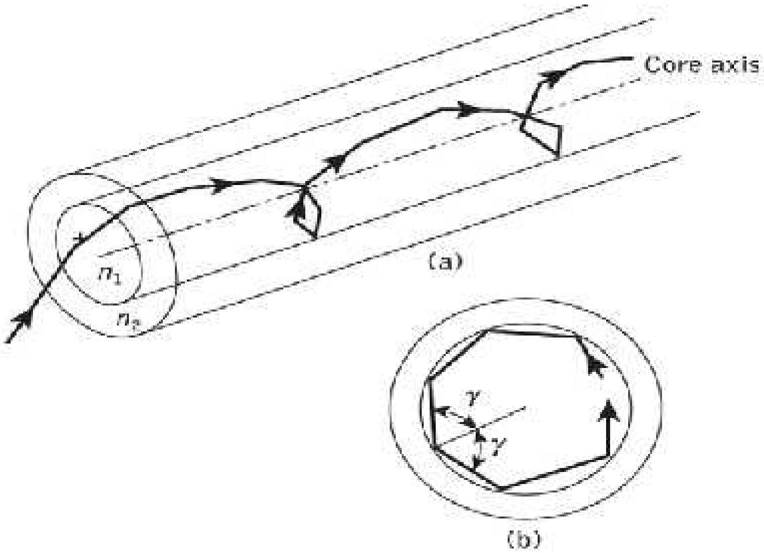




Numerical aperture (NA), shown in above Figure, is the measure of maximum angle at which light rays will enter and be conducted down the fiber. This is represented by the following equation:

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

Skew rays: In a multimode optical fiber, a bound ray that 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) does not intersect the fiber axis is known as a Skew Ray.



Figure, view (a), provides an angled view and view (b) provides a front view.

1. Skew rays are rays that travel through an optical fiber without passing through its axis.

2. A possible path of propagation of skew rays is shown in figure.

3. Skew rays are those rays which follow helical path but they are not confined to a single plane. 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 through the 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 used to describe this type of leaky ray loss.

Cylindrical fiber

1. Modes

When light is guided down a fiber (as microwaves are guided down a waveguide), phase shifts occur at every reflective boundary. There is a finite discrete number of paths down the optical fiber (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 TE (where $E_z = 0$) and TM (where $H_z = 0$) modes are obtained within the dielectric cylinder. The cylindrical waveguide, however, is bounded in two dimensions rather than one. Thus two integers, l and m, are necessary in order to specify the modes, in contrast to the single integer (m) required for the planar guide.

For the cylindrical waveguide, therefore refer to TE_{lm} and TM_{lm} modes. These modes correspond to meridional rays traveling within the fiber. However, hybrid modes where E_z and H_z are nonzero also occur within the cylindrical waveguide.

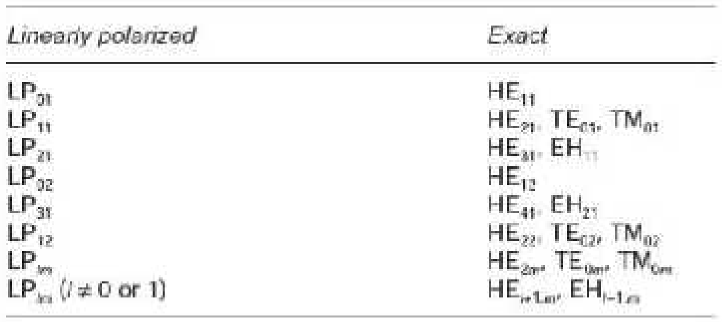
These modes, which result from skew ray propagation within the fiber, are designated HE_{lm} and EH_{lm} depending upon whether the components of H or E make the larger contribution to the transverse (to the fiber axis) field. Thus an exact description of the modal fields in a step index fiber proves somewhat complicated.

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 $\Delta 1$. This corresponds to small grazing angles θ. 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 pairs occur which have almost identical propagation constants. Such modes are said to be degenerate. The superposition of these degenerating modes characterized by a common propagation constant correspond to particular LP modes regardless of their HE, EH, TE or TM field configurations. This linear 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 LPlm mode designations is shown in Table. The mode subscripts l and m are related to the electric field intensity profile for a particular LP mode. There are in general 2l 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 changed from 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. Mode coupling

Thus, so far the propagation aspects of perfect dielectric waveguides were considered. 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 which illustrates two types of perturbation. It may be observed 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.

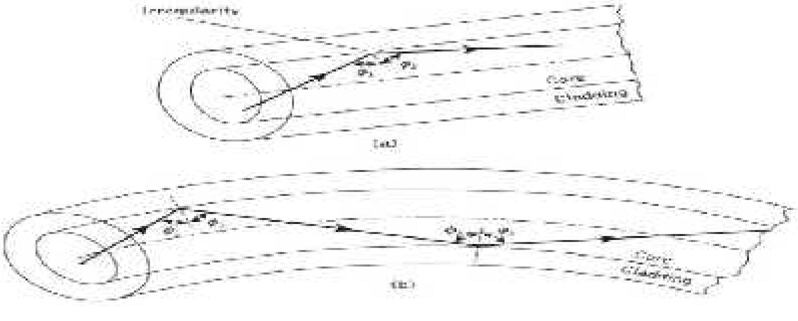


Figure Ray theory illustrations showing two of the possible fiber perturbations which give mode coupling: (a) irregularity at the core–cladding interface; (b) fiber bend

3. Step index fibers

The optical fiber considered in the preceding sections with a core of constant refractive index n_1 and a cladding of a slightly lower refractive index $n_2$is 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 which illustrates the two major types of step index fiber.

Figure shows a multimode step index fiber with a core diameter of around 50µm or greater, which is large enough to allow the propagation of many modes within the fiber core. This is illustrated in Figure by the many different possible ray paths through the fiber. Figure 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 as corresponding to a single ray path only (usually shown as the axial ray) through the fiber. The single-mode step index fiber 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.

The refractive index profile may be defined as

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

in both cases

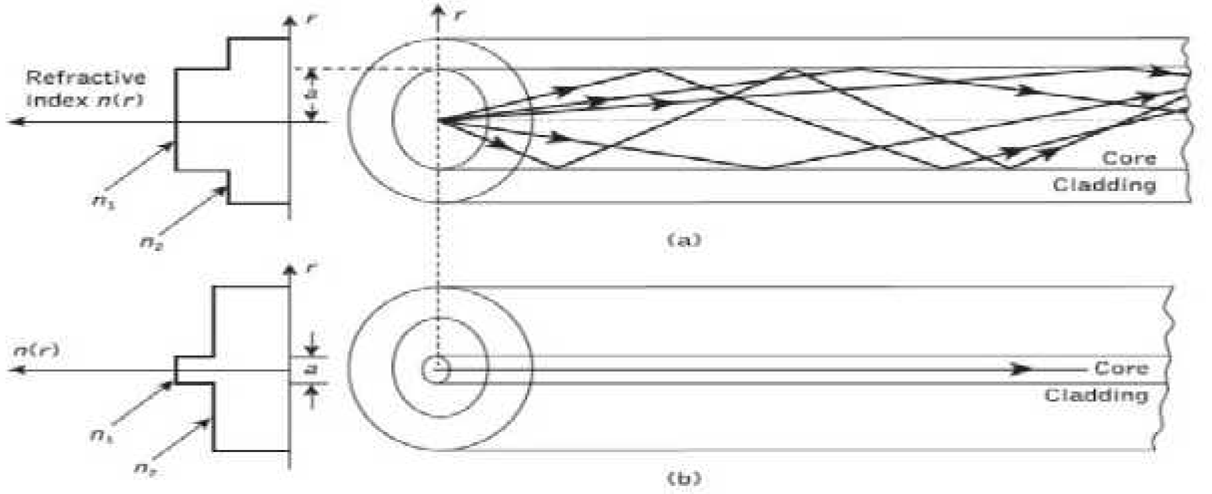


Figure Refractive index profile and ray transmission in step index a) multimode b) single mode

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) Larger numerical apertures, as well as core diameters, facilitating easier coupling to optical sources

c) Lower tolerance requirements on fiber 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 the fiber over its full length. The total number of guided modes or mode volume M_s for a step index fiber is related to the V value for the fiber by the approximate expression that allows an estimate of the number of guided modes propagating in a particular multimode step index fiber.

4. Graded index fibers

Graded index fibers do not have a constant refractive index in the core* but a decreasing core index $n(r)$ with radial distance from a maximum value of$n1$ at the axis to a constant value n_2 beyond the core radius a in the cladding. This index variation may be represented as:

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

where is the relative refractive index difference and α is the profile parameter which gives the characteristic refractive index profile of the fiber core. Equation 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. The graded index profiles which at present produce the best results for multimode optical propagation have a near parabolic refractive index profile core with ~~2. Fibers with such core 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.

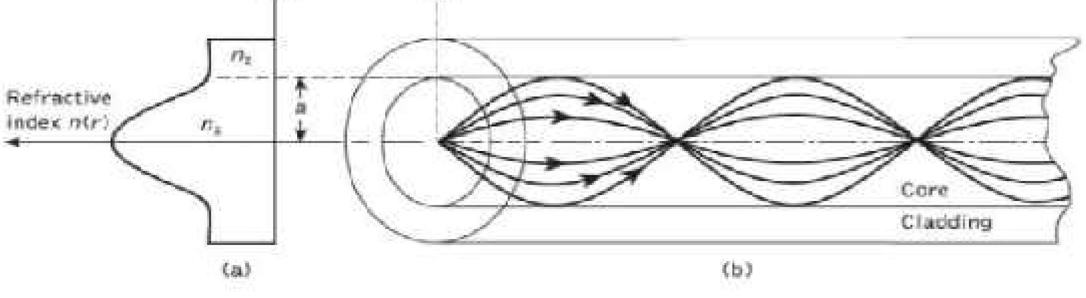


Figure Refractive index profile and ray transmission in multimode graded index

Where, r = Radial distance from fiber axis, a = Core radius, n_1= Refractive index of core, n_2 = Refractive index of cladding, α = Shape of index profile.

Profile parameter α determines the characteristic refractive index profile of fiber core. For this reason in this section, 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. 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 are effectively incident on a large number or high to low index interfaces. This mechanism is illustrated in Figure 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.

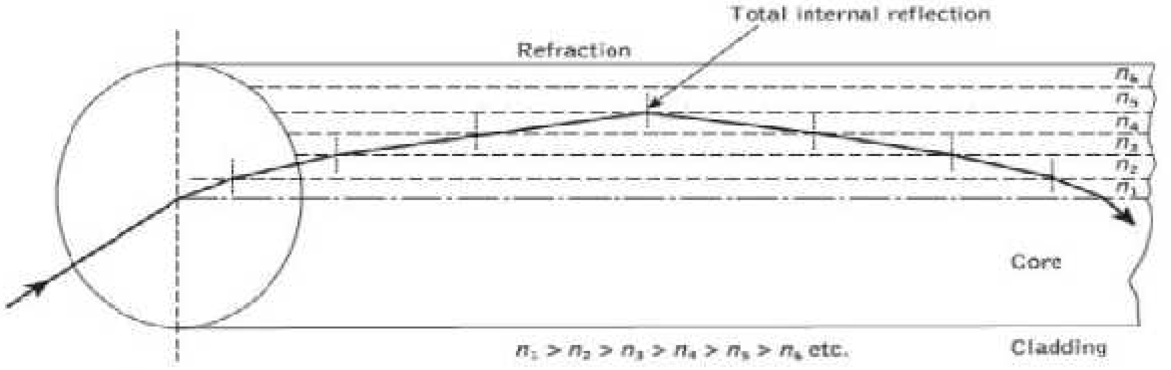


Figure An expanded ray diagram showing refraction

Multimode graded index fibers exhibit far less intermodal dispersion than multimode step index fibers 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.

However, the near axial rays are transmitted through a region of higher refractive index and therefore 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 illustrated in Figure. 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- mode fibers, such multimode graded index fibers have the advantage of large core diameters (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

The advantage of the propagation of a single mode within an optical fiber is that the signal dispersion 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 frequency for the fiber. For single-mode operation, only the fundamental LP01 mode can exist. Hence the limit of single-mode operation depends on the lower limit of guided propagation for the LP11 mode. The cutoff normalized frequency for the LP11 mode in step index fibers occurs at $V_c = 2.405$. Thus single-mode propagation of the LP01 mode in step index fibers is possible over the range:

$$0 \leq V < 2.405$$

As there is no cutoff for the fundamental mode. It must be noted that there are in fact two modes with orthogonal polarization over this range, and the term single-mode applies to propagation of 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 Equation by reduction of the core radius.

1. Cutoff wavelength

It may be noted that single-mode operation only occurs above a theoretical cutoff wavelength λ_c given by:

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

Where V_c- Cut off normalized frequency.

Dividing above equation by

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

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

Thus for step index fiber where V_c=2.405, the cut-off wavelength is given by

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

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 higher order LP11 mode 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 in order to enhance the fundamental mode confinement, but sufficiently distant from cutoff so that no power is transmitted in the second-order LP11 mode.

2. Mode-field diameter and spot size

Many properties of the fundamental mode are determined by the radial extent of its electromagnetic field including losses at launching and jointing, micro bend losses, waveguide dispersion and the width 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 λ_c, 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) ω0. Hence MFD = $2\omega_0$, where ω_0 is the nominal half width of the input excitation.

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 and hence alternative techniques have been proposed. However, the problem of defining the MFD and spot size for non-Gaussian field distributions is difficult one and at least eight definitions exist**.**

3. Effective refractive index

The rate of change of phase of the fundamental LP01 mode propagating along a straight fiber is determined by the phase propagation constant. It is directly related to the wavelength of the LP01 mode λ_{01} by the factor 2π, since β gives the increase in phase angle per unit length. Hence:

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

Morever, 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 vaccum propagation constant.

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

Hence, the wavelength of the fundamental mode is smaller than the vaccum wave by the factor 1/ n_{eff} ,where

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

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 can therefore 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 $n2k$ (i.e. the cladding wave number) and the effective index will be similar to the refractive index of the 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 nlk. 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 $n_2 < n\mathrm{eff} < n_1$.

4. Group delay and mode delay factor

The transit time or group delay τ_g for a light pulse propagating along a unit length of fiber is the inverse of the group velocity, υ_g

$$\tau_g = \frac{1}{\upsilon_g} = \frac{d\beta}{d\omega} = \frac{1}{c}\frac{d\beta}{dk}$$

The group index of a uniform plane wave propagating in a homogenous medium has been identified as

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

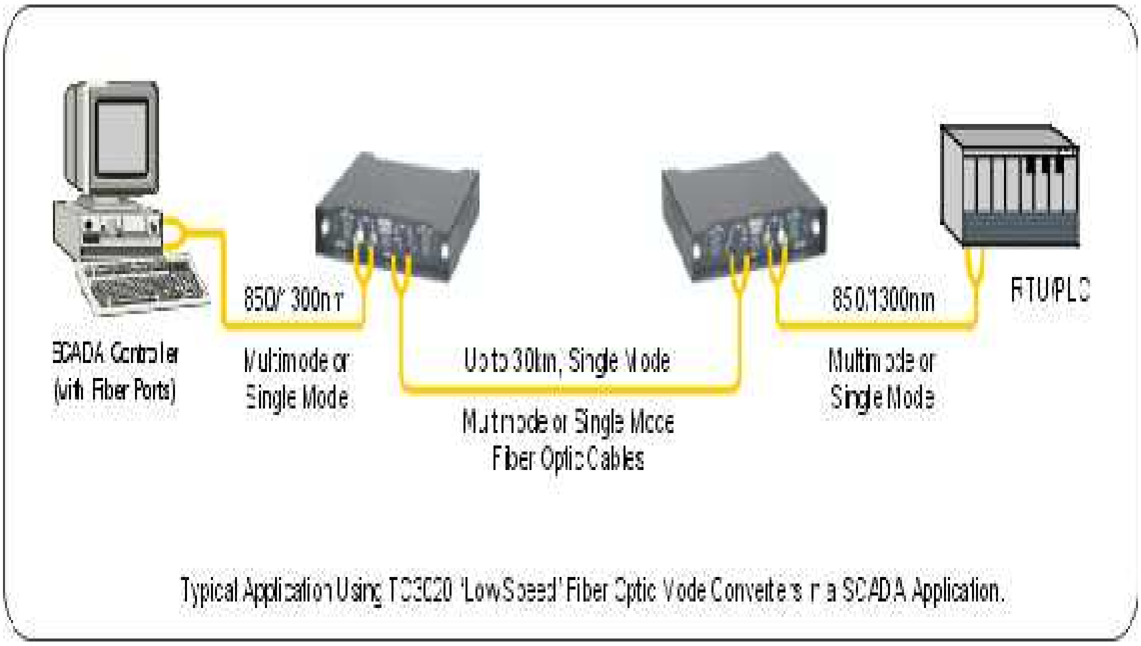
However, for a single mode fiber, it is usual to define an effective group index by

$$N_{ge} = \frac{c}{\upsilon_g}$$

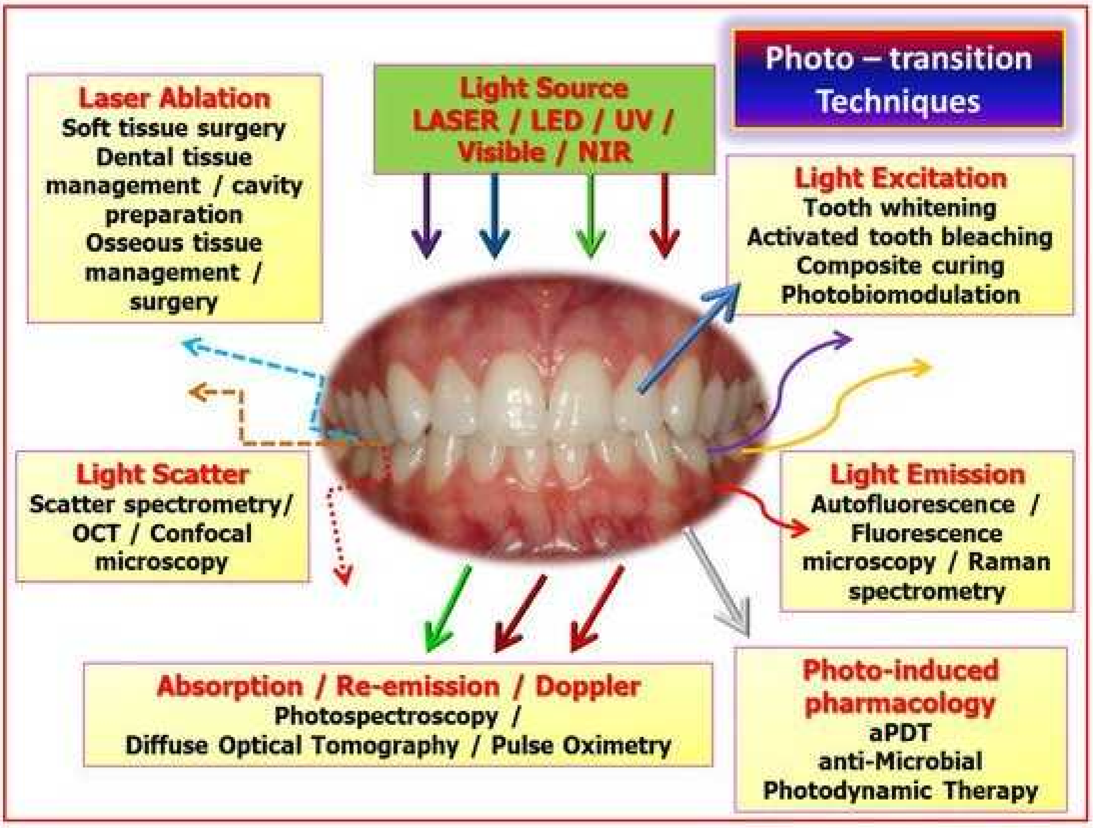
Hence, where υ_g is considered to be the group velocity of the fundamental fiber mode. Hence, the specific group delay of the fundamental fiber mode becomes:

$$\tau_g = \frac{N_{ge}}{c}$$

APPLICATIONS



Examples of Typical Application of Fiber Optic Mode in SCADA application



Examples of Application of optical fiber in Dentistry

POST TEST-MCQ TYPE

1. What is refraction?
a) Bending of light waves
b) Reflection of light waves
c) Diffusion of light waves
d) Scattering of light waves

2. The phenomenon which occurs when an incident wave strikes an interface at an angle greater than the critical angle with respect to the normal to the surface is called as
a) Refraction
b) Partial internal reflection
c) Total internal reflection
d) Limiting case of refraction

3. A monochromatic wave propagates along a waveguide in z direction. These points of constant phase travel in constant phase travel at a phase velocity Vp is given by?
a) Vp=ω/β
b) Vp=ω/c
c) Vp=C/N
d) Vp=mass/acceleration

4. Which law gives the relationship between refractive index of the dielectric?
a) Law of reflection
b) Law of refraction (Snell's Law)
c) Millman's Law
d) Huygen's Law

5. The light sources used in fibre optics communication are
a) LED's and Lasers
b) Phototransistors
c) Xenon lights
d) Incandescent

6. Which ray passes through the axis of the fiber core?
a) Reflected
b) Refracted
c) Meridional
d) Skew

7. Light incident on fibers of angles___the acceptance angle do not propagate into the fiber.
a) Less than
b) Greater than
c) Equal to
d) Less than and equal to

8. The ratio of speed of light in air to the speed of light in another medium is called as
a) Speed factor
b) Dielectric constant
c) Reflection index
d) Refraction index

9. When a ray of light enters one medium from another medium, which quality will not change?
a) Direction
b) Frequency
c) Speed
d) Wavelength

10. What is the numerical aperture of the fiber if the angle of acceptance is 16 degree?
a) 0.50
b) 0.36
c) 0.20
d) 0.27

11. For lower bandwidth applications
a) Single mode fiber is advantageous
b) Photonic crystal fibers are advantageous
c) Coaxial cables are advantageous
d) Multimode fiber is advantageous

12. Meridional rays in graded index fibers follow
a) Straight path along the axis
b) Curved path along the axis
c) Path where rays changes angles at core-cladding interface
d) Helical path

13. Skew rays follow a
a) Hyperbolic path along the axis
b) Parabolic path along the axis
c) Helical path
d) Path where rays changes angles at core-cladding interface

14. What is needed to predict the performance characteristics of single mode fibers?
a) The intermodal delay effect
b) Geometric distribution of light in a propagating mode
c) Fractional power flow in the cladding of fiber
d) Normalized frequency

15. Which equation is used to calculate MFD?
a) Maxwell’s equations
b) Peterman equations
c) Allen Cahn equations
d) Boltzmann’s equations

16. he difference between the modes’ refractive indices is called as
a) Polarization
b) Cutoff
c) Fiber birefringence
d) Fiber splicing

17. How many propagation modes are present in single mode fibers?
a) One
b) Two
c) Three
d) Five

18. A device that reduces the intensity of light in optical fiber communications is
a) Compressor
b) Optical attenuator
c) Barometer
d) Reducer

19. The core of an optical fiber has a
a) Lower refracted index than air
b) Lower refractive index than the cladding
c) Higher refractive index than the cladding
d) Similar refractive index with the cladding

20. One of the following materials is sensitive to light. Identify it.
a) Photoresist
b) Photosensitive
c) Light Sensitive
d) Maser

21. If a mirror is used to reflect light, the reflected light angle is **____** as the incident angle
a) Smaller
b) Larger
c) The same
d) Independent

22. This is not a part of the optical spectrum. Identify it.
a) infrared
b) ultraviolet
c) visible color
d) x-rays

23. Which type of fiber has the highest modal dispersion.
a) Step-index multimode
b) Graded index multimode
c) Step-index single mode
d) Graded index mode

24. What is a specific path the light takes in an optical fiber corresponding to a certain angle and number of reflection?
a) Mode
b) Grade
c) Numerical Aperture
d) Dispersion

CONCLUSION

In this unit, an understanding of optical fiber communication link, structure, propagation and transmission properties of an optical fiber and the Estimate the losses and analyze the propagation characteristics of an optical signal in different types of fibers was done. The Introduction to Optical Fibers, its types and applications were discussed.

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ASSIGNMENT

1. Describe the Ray theory transmission.
2. Describe Single-mode fiber and its mode field diameter.
3. Describe in detail the Classification of fibers or Compare the structure and characteristics of step index and graded index fiber structures.
4. Derive the expression for linearly polarized modes in optical fibers and obtain the expression for normalized frequency.
5. A step index multimode fiber with a numerical aperture of 0.2 support approximately 1000 modes at 850 nm wavelength. What is the diameter of its core? How many modes does the fiber support at 850 nm and 1550 nm.
6. Draw the block diagram of optical fiber transmission link and explain.

AIM & OBJECTIVES

- To learn the basic elements of optical fiber transmission link, fiber modes configurations and structures.
- To understand the different kind of losses, signal distortion, SM fibers.
- To learn the various optical sources, materials and fiber splicing.
- To learn the fiber optical receivers and noise performance in photo detector.

PRE TEST-MCQ TYPE

1. What does ISI stand for in optical fiber communication?
a) Invisible size interference
b) Infrared size interference
c) Inter-symbol interference
d) Inter-shape interference

2. 3dB optical bandwidth is always ___________ the 3dB electrical bandwidth.
a) Smaller than
b) Larger than
c) Negligible than
d) Equal to

3. In waveguide dispersion, refractive index is independent of
a) Bit rate
b) Index difference
c) Velocity of medium
d) Wavelength

4. After Total Internal Reflection the Meridional ray
a) Makes an angle equal to acceptance angle with the axial ray
b) Makes an angle equal to critical angle with the axial ray
c) Travels parallel equal to critical angle with the axial ray
d) Makes an angle equal to critical angle with the axial ray

5. How many mechanisms are there which causes absorption?
a) One
b) Three
c) Two
d) Four

UNIT II SIGNAL DEGRADATION OPTICAL FIBERS

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

THEORY

Introduction

One of the important property of optical fiber is signal attenuation. It is also known as fiber loss or signal loss. The signal attenuation of fiber determines the maximum distance between transmitter and receiver. The attenuation also determines the number of repeaters required, maintaining repeater is a costly affair. Another important property of optical fiber is distortion mechanism. As the signal pulse travels along the fiber length it becomes 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

Attenuation is a measure of decay of signal strength or loss of light power that occurs as light pulses propagate through the length of the fiber. In optical fibers the attenuation is mainly caused by two physical factors absorption and scattering losses. Absorption is because of fiber material and scattering due to structural imperfection within the fiber. Nearly 90% of total attenuation is caused by Rayleigh scattering only. Microbending of optical fiber also contributes to the attenuation of signal.

The rate at which light is absorbed is dependent on the wavelength of the light and the characteristics of particular glass. Glass is a silicon compound, by adding different additional chemicals to the basic silicon dioxide the optical properties of the glass can be changed.

The Rayleigh scattering is wavelength dependent and reduces rapidly as the wavelength of the incident radiation increases. 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.

Attenuation Units

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

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

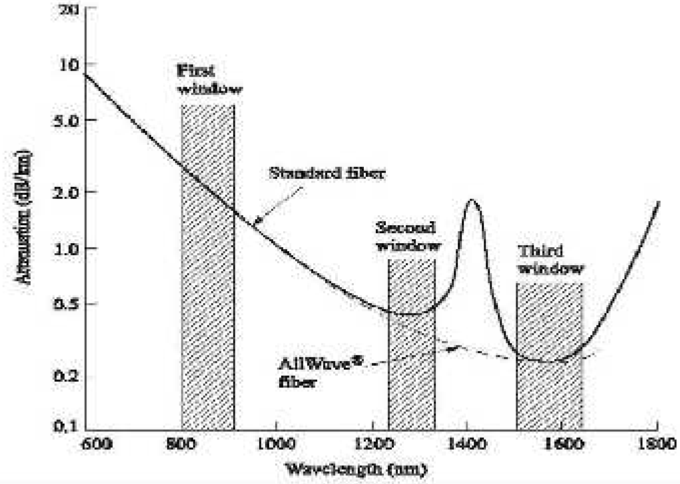
where, α_p is fiber attenuation constant (per km).

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

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

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

This parameter is known as fiber loss or fiber attenuation. Attenuation is also a function of wavelength. Optical fiber wavelength as a function of wavelength is shown in Figure.



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.

Figure Optical fiber wavelength as a function of wavelength

Absorption

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

Absorption in optical fiber is caused by these three mechanisms.

1. Absorption by atomic defects in the glass composition

2. Extrinsic absorption by impurity atoms in the glass material

3. Intrinsic absorption by the basic constituent atoms of the fiber material.

Absorption by Atomic Defects

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

The absorption effect is most significant when fiber is exposed to ionizing radiation in nuclear reactor, medical therapies, space missions etc. The radiation dames the internal structure of fiber. The damages are proportional to the intensity of ionizing particles. This results in increasing attenuation due to atomic defects and absorbing optical energy. The total dose a material receives is expressed in rad (Si), this is the unit for measuring radiation absorbed in bulk silicon. 1 rad (Si) = 0.01 J.kg. The higher the radiation intensity more the attenuation as shown in Figure

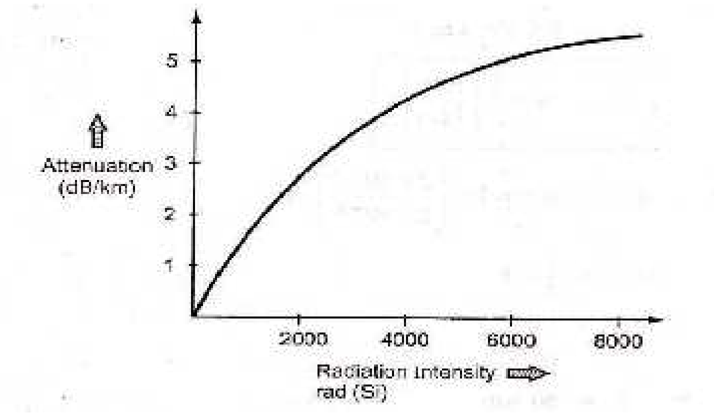


Figure ionizing radiation intensity vs fiber attenuation

Extrinsic Absorption

Extrinsic absorption occurs due to electronic transitions between the energy level and because of charge transitions from one ion to another. A major source of attenuation is from transition of metal impurity ions such as iron, chromium, cobalt and copper. These losses can be upto 1 to 10 dB/km. The effect of metallic impurities can be reduced by glass refining techniques. Another major extrinsic loss is caused by absorption due to OH (Hydroxil) ions impurities dissolved in glass. Vibrations occur at wavelengths between 2.7 and 4.2 µm. The absorption peaks occurs at 1400, 950 and 750 nm. These are first, second and third overtones respectively. Figure shows absorption spectrum for OH group in silica. Between these absorption peaks there are regions of low attenuation.

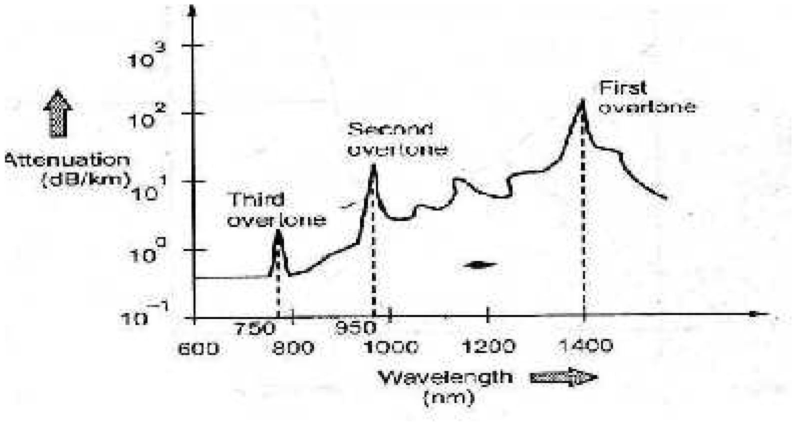


Figure Absorption spectra for OH groups

Intrinsic Absorption

Intrinsic absorption occurs when material is in absolutely pure state, no density variation and in homogenities. Thus intrinsic absorption sets the fundamental lower limit on absorption for any particular material. Intrinsic absorption results from electronic absorption bands in UV region and from atomic vibration bands in the near infrared region. The electronic absorption bands are associated with the band gaps of amorphous glass materials. Absorption occurs when a photon interacts with an electron in the valence band and excites it to a higher energy level. UV absorption decays exponentially with increasing wavelength (λ). 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 is strong because of many bonds present in the fiber. The ultraviolet loss at any wavelength is expressed as,

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

where, x is mole fraction of GeO_2. λ is operating wavelength. α_{uv} is in dB/km.

The loss in infrared (IR) region (above 1.2 µm) is given by expression

The expression is derived for GeO_2-SiO_2 glass fiber.

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

Rayleigh Scattering Losses

Scattering losses exists in optical fibers because of microscopic variations in the material density and composition. As glass is composed by randomly connected network of molecules and several oxides (e.g. 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.

Rayleigh scattering of light is due to small localized changes in the refractive index of the core and cladding material. There are two causes during the manufacturing of fiber. The first is due to slight fluctuation in mixing of ingredients. The random changes because of this are impossible to eliminate completely. The other cause is slight change in density as the silica cools and solidifies. When light ray strikes such zones it gets scattered in all directions. The amount of scatter depends on the size of the discontinuity compared with the wavelength of the light so the shortest wavelength (highest frequency) suffers most scattering. The below figure shows graphically the relationship between wavelength and Rayleigh scattering loss.

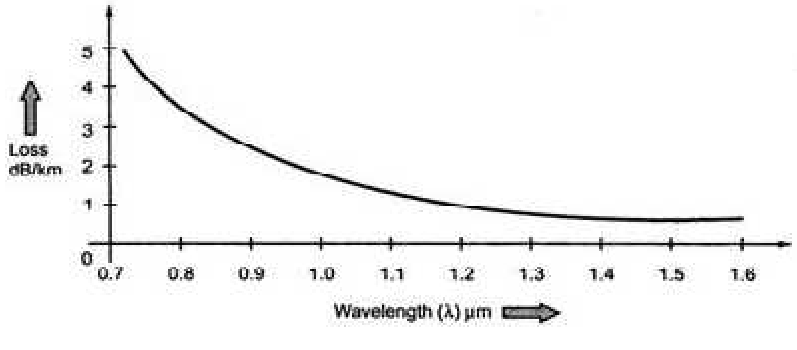


Figure Scattering loss

Scattering loss for single component glass is given by,

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

where, n = Refractive index, B = Boltzmann’s constant, β_T = Isothermal compressibility of material, T_f = Temperature at which density fluctuations are frozen into the glass as it solidifies (fictive temperature)

Another form of equation is

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

where, P = Photoelastic coefficient

where, δ_n^2 = Mean square refractive index fluctuation

δv = Volume of fiber

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

Mie Scattering

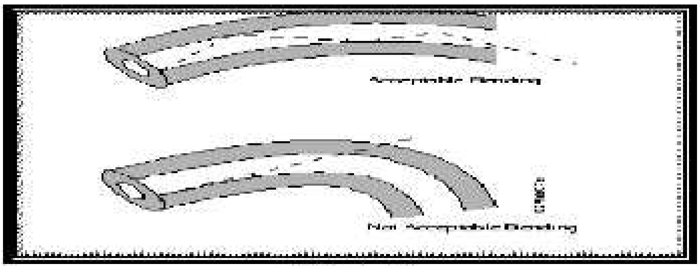
Linear scattering also occurs at in homogenities and these arise from imperfections in the fiber’s geometry, irregularities in the refractive index and the presence of bubbles etc. caused during manufacture. Careful control of manufacturing process can reduce Mie scattering to insignificant levels.

Bending Loss

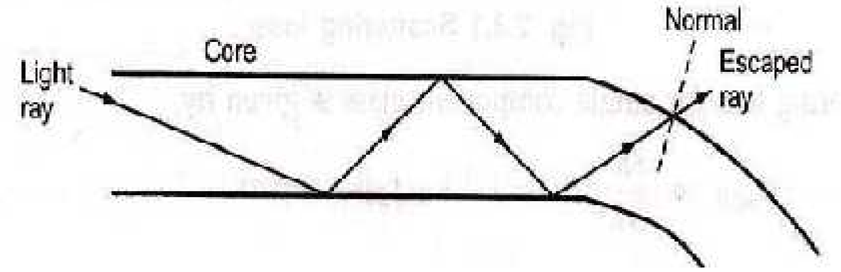
Radiative losses occur whenever an optical fiber undergoes a bend of finite radius of curvature. Fibers can be subjected to two types of bends:

a) Macroscopic bends (having radii that are large as compared with the fiber diameter)

b) Random microscopic bends of fiber axis Losses due to curvature and losses caused by an abrupt change in radius of curvature are referred to as ‘bending losses.’ The sharp bend of a fiber causes insignificant radiative losses and there is also possibility of mechanical failure.



Bending loss



As the core bends the normal will follow it and the ray will now find itself on the wrong side of critical angle and will escape. The sharp bends are therefore avoided. The radiation loss from a bent fiber depends on –Field strength of certain critical distance x_C from fiber axis where power is lost through radiation.

The radius of curvature R.

The higher order modes are less tightly bound to the fiber core, the higher order modes radiate out of fiber firstly. For multimode fiber, the effective number of modes that can be guided by curved fiber is

where, α is graded index profile.

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

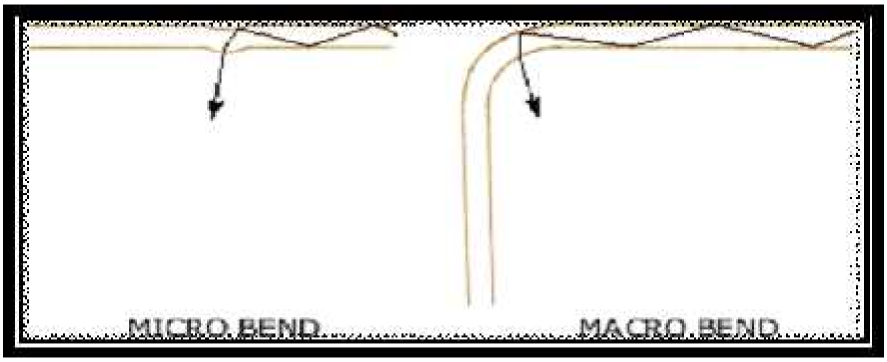
$$N_\infty = \frac{\alpha}{\alpha+2}(n_1\, k\, a)^2\Delta$$

N_∞ is total number of modes in a straight fiber.

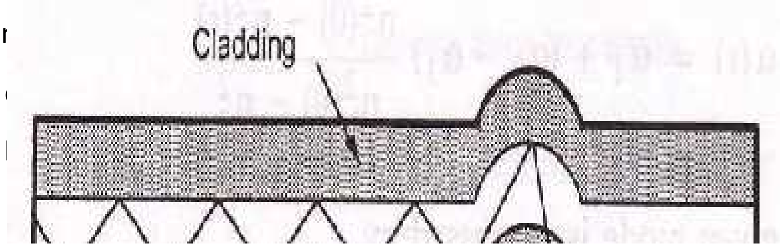
Micro bending Loss

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

Micro bending losses can be minimized by placing a compressible jacket over the fiber. When external forces are applied to this configuration, the jacket will be deformed but the fiber will tend to stay relatively straight. Microbending is a loss due to small bending or distortions. This small microbending is not visible. The losses due to this are temperature related, tensile related or crush related.



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; the field tail would have to move faster than the speed of light to keep up with the 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 minimized by not exceeding the long term bend radii.

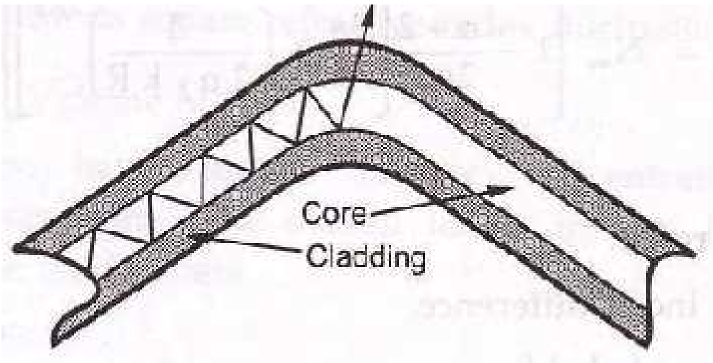


Figure macrobending loss

Core and Cladding Loss

Since the core and cladding have different indices of refraction hence they have different attenuation coefficients α_1 and α_2 respectively.

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

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

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

For low-order modes, the expression reduced to

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

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

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

The loss for a given mode is expressed by,

$\propto_{Graded\ Index} = \frac{\int_0^\infty \propto(r)\,P(r)\,r\,dr}{\int_0^\infty P(r)\,r\,dr}$ where, P(r) is power density of that model at radial distance r.

Signal Distortion in Optical Waveguide

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

Information Capacity Determination

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

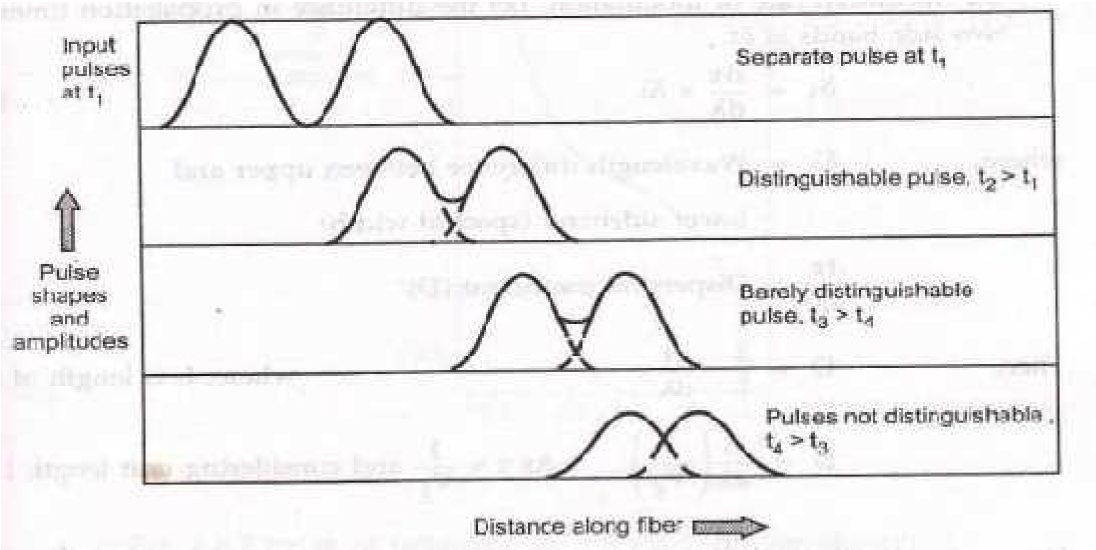
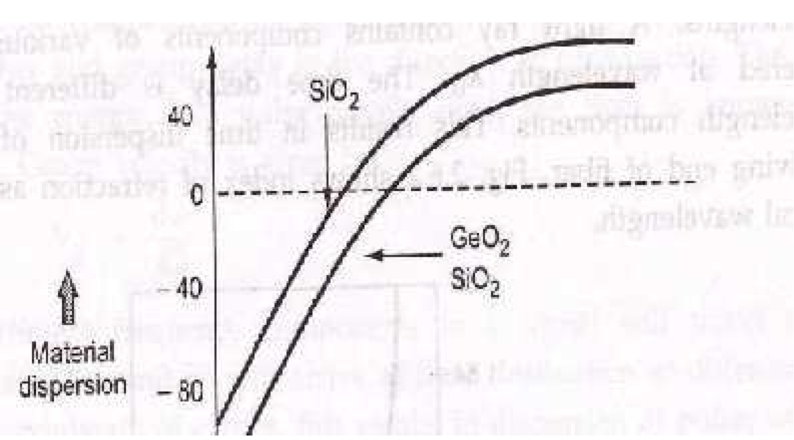


Figure Dispersion and Attenuation in fiber

Group Delay

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

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



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

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

$\delta\tau$ Where, = Wavelength diff (spectral width)

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

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

where, L is length of fiber.

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

and considering unit length L = 1. Now

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

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

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

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

Dispersion is measured in picoseconds per nanometer per kilometer.

Material Dispersion

Material dispersion is also called as chromatic dispersion. Material dispersion exists due to change in index of refraction for different wavelengths. A light ray contains 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. Figure shows index of refraction as a function of optical wavelength. The material dispersion for unit length (L = 1) is given by

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

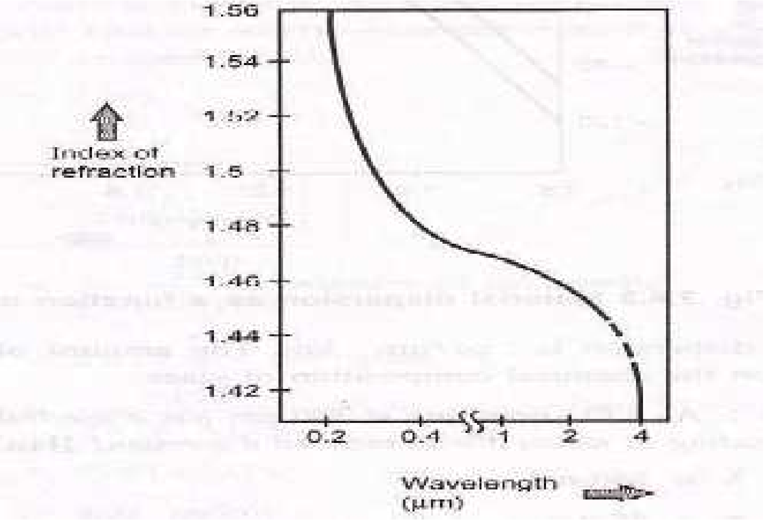


Figure Index of refraction as a function of wavelength

where, c = Light velocity, λ = Center wavelength

$\frac{d^2n}{d\lambda^2}$ = Second derivative of index of refraction w.r.t wavelength Negative sign shows that the upper sideband signal (lowest wavelength) arrives before the lower sideband (highest wavelength). The unit of dispersion is : ps/nm . km. The amount of material dispersion depends upon the chemical composition of glass.

Waveguide Dispersion

Waveguide dispersion is caused by the difference in the index of refraction between the core and cladding, resulting in a 'drag' effect between the 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. The group delay (τ_{wg}) arising due to waveguide dispersion

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

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

Normalized frequency V,

$$\mathrm{V} = \mathrm{ka}(\mathrm{n}_1^2 - \mathrm{n}_2^2)^{\frac{1}{2}}$$

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

The second term $\frac{\mathrm{d}(\mathrm{V_b})}{\mathrm{dV}}$ is waveguide dispersion and is mode dependent term..

As frequency is a function of wavelength, the group velocity of the energy varies with frequency. The produces additional losses (waveguide dispersion) and the propagation constant (b) varies with wavelength, the causes of which are independent of material dispersion.

Chromatic Dispersion

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. A graph of effective refractive index against wavelength illustrates the effects of material, chromatic and waveguide dispersion.

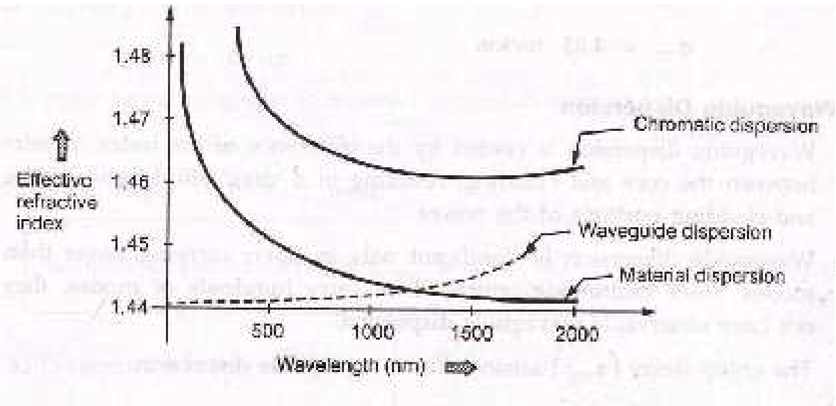


Figure Graph of refractive index against wavelength showing effects of chromatic, waveguide and material dispersion

Material dispersion and waveguide dispersion effects vary in vary in opposite senses as the wavelength increased, but at an optimum wavelength around 1300 nm, two effects almost cancel each other and chromatic dispersion is at minimum. Attenuation is therefore also at minimum and makes 1300 nm a highly attractive operating wavelength.

Modal Dispersion

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. Modal dispersion takes place in multimode fibers. It is moderately present in graded index fibers and almost eliminated in single mode step index fibers.

Modal dispersion is given by,

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

where Δt_{modal} = Dispersion

n1 = Core refractive index

Z = Total fiber length

c = Velocity of light in air

Fractional refractive index

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

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

Polarization Mode Dispersion (PMD)

Different frequency component of a pulse acquires different polarization state (such as linear polarization and circular polarization). This result in pulse broadening is known as polarization mode dispersion (PMD). PMD is the limiting factor for optical communication system at high data rates. The effects of PMD must be compensated.

Pulse Broadening in GI 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, will travel faster than the lower order modes travelling in high refractive index region. If the index profile is carefully controlled, then the transit times of the individual modes will be identical, so eliminating modal dispersion. The r.m.s pulse broadening is given as:

$$\sigma = \left(\sigma_{intermodal}^2 + \sigma_{intermodal}^2\right)^{1/2}$$

where, σintermodal – R.M.S pulse width due to intermodal delay distortion., $\sigma_{intermodal}$ – R.M.S pulse width resulting from pulse broadening within each mode.

The intermodal delay and pulse broadening are related by expression given by Personick.

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

Where τg is group delay.From this the expression for intermodal pulse broadening is given as:

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

$$\left[c_1^2 + \frac{4c_1c_2(\propto+1)}{2\propto+1} + \frac{16\Delta^2 c_2^2(\propto+1)^2}{(5\propto+2)(3\propto+2)}\right]^{1/2}$$

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

The intramodal pulse broadening is given as :

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

Where σλ is spectral width of optical source.

Solving the expression gives :

$$\sigma_{intramodal}^{2} = \frac{L}{c} \cdot \frac{\sigma\lambda}{\lambda} \Bigg[\Bigg(-\lambda^{2} \frac{d^{2}n_{1}}{d\lambda^{2}} \Bigg)^{2} - N_{1}c_{1}\Delta$$

$$\Bigg(2\lambda^{2} \frac{d^{2}n_{1}}{d\lambda^{2}} \cdot \frac{\alpha}{\alpha+1} - N_{1}c_{1}\Delta \frac{4\alpha^{2}}{(\alpha+2)(3\alpha+2)} \Bigg) \Bigg]^{1/2}$$

Mode Coupling

After certain initial length, the pulse distortion increases less rapidly because of mode coupling. 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 = Lc, mode coupling length, over Lc = 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. σ_c is pulse broadening under mode coupling. σ_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 for various coupling losses are shown

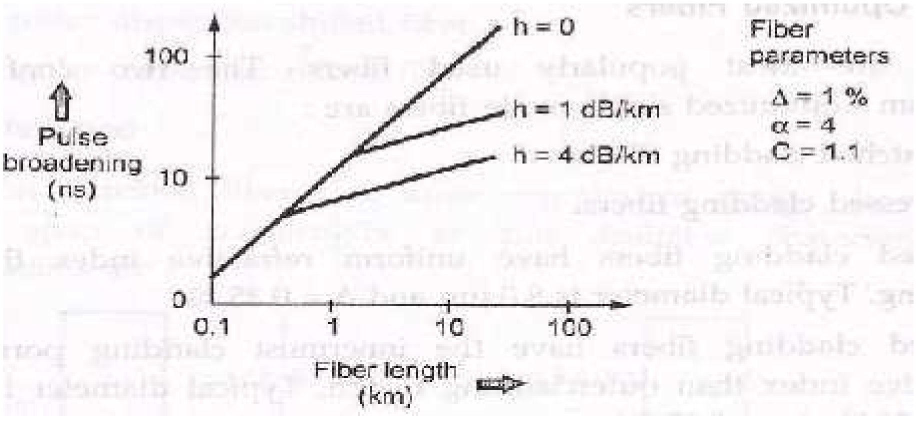


Figure Mode coupling effects on pulse broadening

Design Optimization

Features of single mode fibers are: Longer life, Low attenuation, Signal Transfer quality is good, Modal noise is absent, Largest BW-distance product. Basic design – optimization includes the following: Dispersion, Mode field, Diameter, bending loss, Refractive index profile, Cut-off wavelength.

Refractive Index Profile

Dispersion of single mode silica fiber is lowest at 1300 nm while its attenuation is minimum 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-cladding refractive.

1300nm – Optimized Fibers

These are most popularly used fibers. The two configurations of 1300 nm – optimized single mode fibers are

- Matched cladding fibers.
- Dressed cladding fibers.

Matched cladding fibers have uniform refractive index throughout its cladding. Typical diameter is 9.0 µm and $\Delta = 0.35$ %. Dressed cladding fibers have the innermost cladding portion has low refractive index than outer cladding region. Typical diameter is 8.4 µm and $\Delta_1 = 0.25$ %, $\Delta_2 = 0.12$ %.

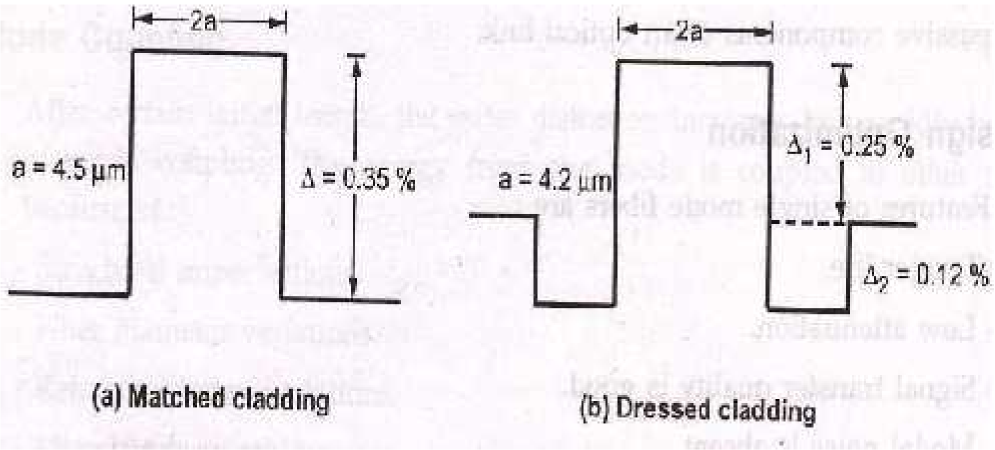


Figure 1300nm – optimized refractive index

Dispersion Shifted Fibers

The addition of wavelength and material dispersion can shift the zero dispersion point of longer wavelength. Two configurations of dispersion shifted fibers are

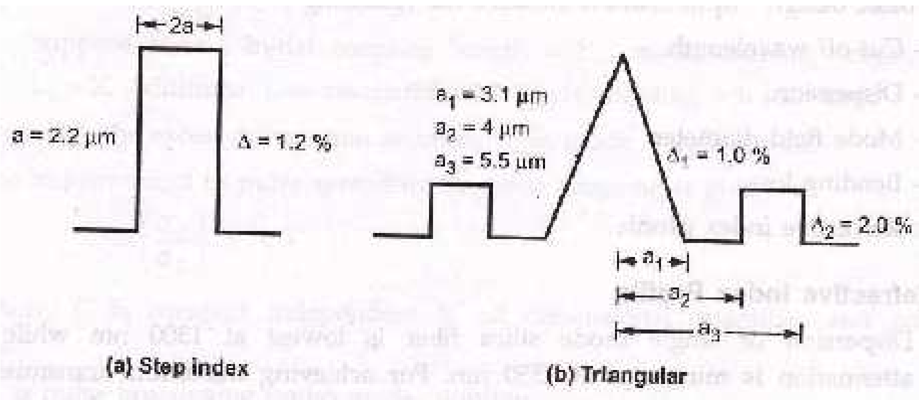


Figure Dispersion shifted fibers

Dispersion Flattened

Dispersion flattened fibers are more complex to design. It offers much broader span of wavelengths to suit desirable characteristics. Two configurations are:

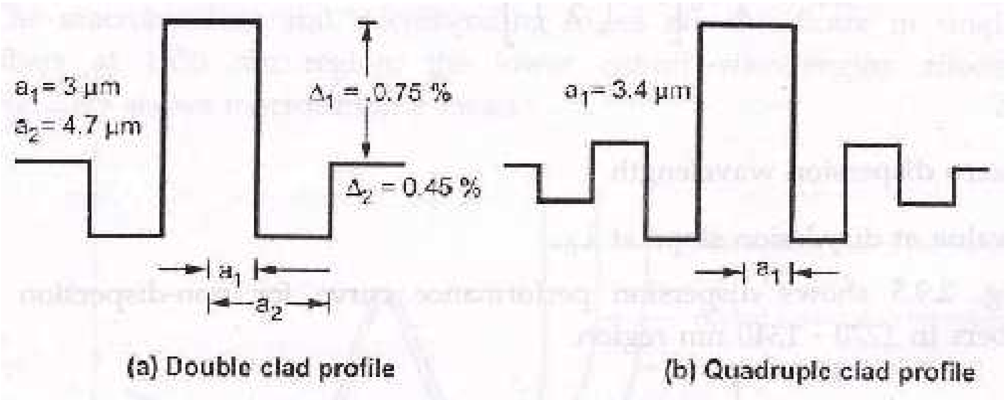


Figure Dispersion Flattened

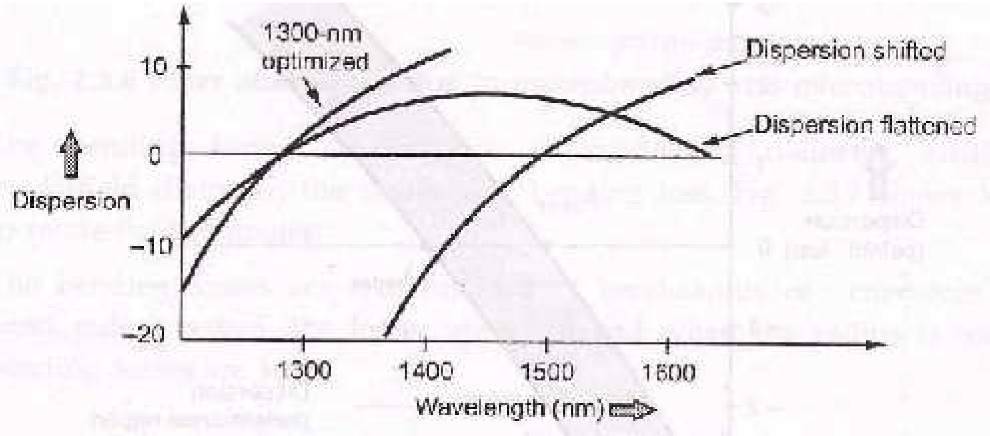


Figure Total resultant dispersion

Dispersion Calculations

The total dispersion consists of material and waveguide dispersions. The resultant intermodal dispersion is given as,

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

Where, τ is group delay per unit length of fiber. The broadening σ of an optical pulse is given

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

Where, $\sigma\lambda$ is half power spectral width of source.

As the dispersion varies with wavelength and fiber type, Different formulae are used to calculate dispersions for variety of fiber at different wavelength.

For Non-dispersion shifted fiber between 1270 nm to 1340 nm wavelength, the expression for dispersion is given as :

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

Where, λ_0 is zero dispersion wavelength. S_0 is value at dispersion slop at λ_0.

The below figure shows dispersion performance curve for non-dispersion shifted fibers in 1270 – 1340 nm region.

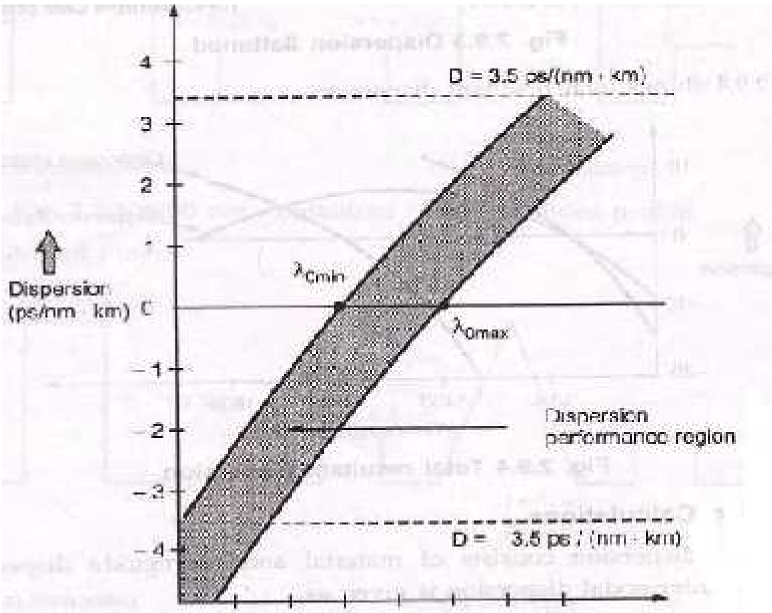


Figure Wavelength vs dispersion

Maximum dispersion specified as 3.5 ps/(nm . km) marked as dotted line in Figure

The cut-off frequency of an optical fiber

The cut-off frequency of an optical fiber is determined not only by the fiber itself (modal dispersion in case of multimode fibers and waveguide dispersion in case of single mode fibers) but also by the amount of material dispersion caused by the spectral width of transmitter.

Bending Loss Limitations

The macrobending and microbending losses are significant in single mode fibers at 1550 nm region, the lower cut-off wavelengths affects more. Figure shows macrobending losses.

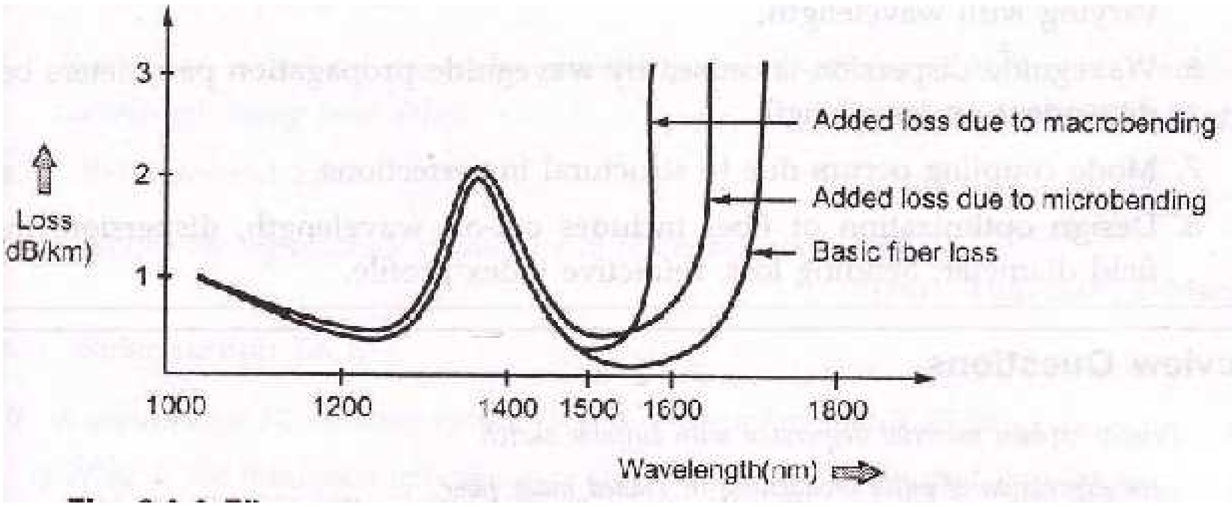
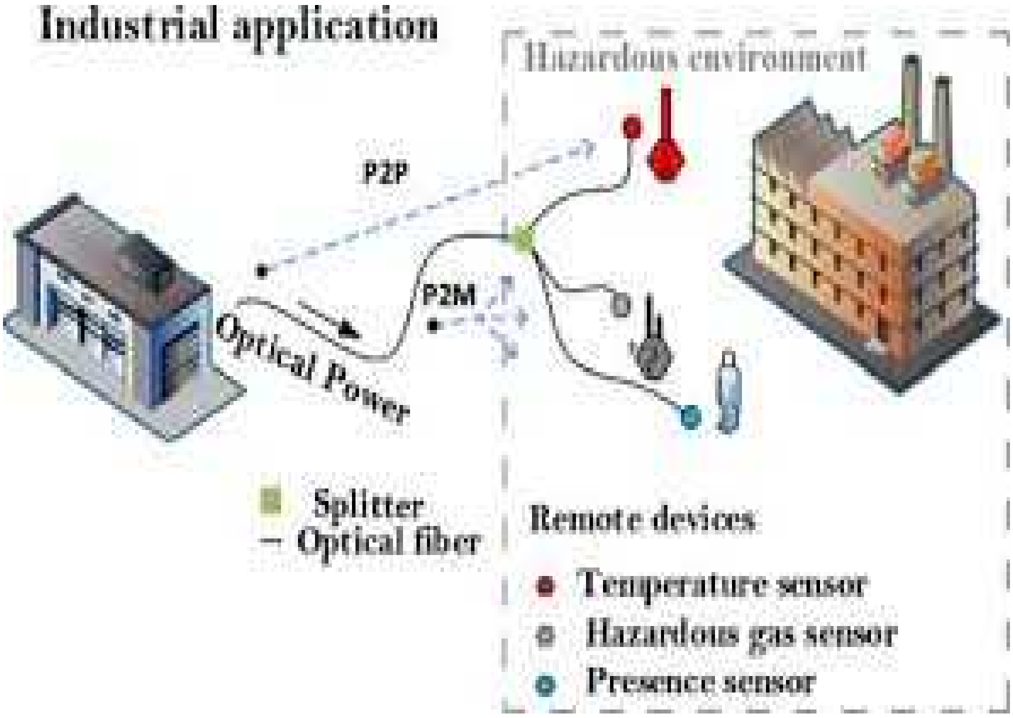


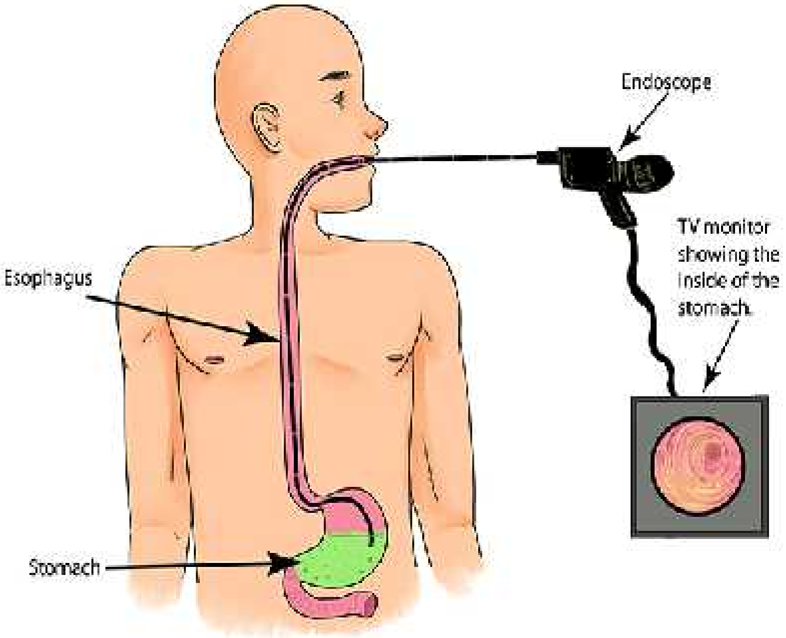
Figure Fiber attenuation due to microbending and macrobending

The bending losses are function of mode-filed diameter, smaller the mode-field diameter, the smaller the bending loss. Figure shows loss due to mode-field diameter. The bending 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.

APPLICATIONS



Examples of Remote Optical Powering in Industrial Application



Examples of Medical use of Fiber Optics (Endoscopy)

POST TEST-MCQ TYPE

1. Which of the following statements best explain the concept of material absorption?
a) A loss mechanism related to the material composition and fabrication of fiber
b) A transmission loss for optical fibers
c) Results in attenuation of transmitted light
d) Causes of transfer of optical power

2. Polarization modal noise can **_________** the performance of communication system.
a) Degrade
b) Improve
c) Reduce
d) Attenuate

3. Absorption losses due to atomic defects mainly include
a) Radiation
b) Missing molecules, oxygen defects in glass
c) Impurities in fiber material
d) Interaction with other components of core

4. The effects of intrinsic absorption can be minimized by
a) Ionization
b) Radiation
c) Suitable choice of core and cladding components
d) Melting

5. Which of the following is not a metallic impurity found in glass in extrinsic absorption?
a) Fe^{2+}
b) Fe^{3+}
c) Cu
d) Si

6. A multimode fiber has refractive indices n1 = 1.15, n2 = 1.11 and an operating wavelength of 0.7μm. Find the radius of curvature?

a) 8.60μ_m
b) 9.30μ_m
c) 9.1μ_m
d) 10.2μ_m

7. A single mode fiber has refractive indices n1=1.50, n2 = 2.23, core diameter of 8μm, wavelength = 1.5μm cutoff wavelength = 1.214μm. Find the radius of curvature?
a) 12 mm
b) 20 mm
c) 34 mm
d) 36 mm

8. How the potential macro bending losses can be reduced in case of multimode fiber?
a) By designing fibers with large relative refractive index differences
b) By maintaining direction of propagation
c) By reducing the bend
d) By operating at larger wavelengths

9. Rayleigh scattering and Mie scattering are the types of
a) Linear scattering losses
b) Non-linear scattering losses
c) Fiber bends losses
d) Splicing losses

10. Dominant intrinsic loss mechanism in low absorption window between ultraviolet and infrared absorption tails is
a) Mie scattering
b) Rayleigh scattering
c) Stimulated Raman scattering
d) Stimulated Brillouin scattering

11. The scattering resulting from fiber imperfections like core-cladding RI differences, diameter fluctuations, strains, and bubbles is?
a) Rayleigh scattering
b) Mie scattering
c) Stimulated Brillouin scattering
d) Stimulated Raman scattering

12. Mie scattering has in-homogeneities mainly in
a) Forward direction
b) Backward direction
c) All direction
d) Core-cladding interface

13. Raman and Brillouin scattering are usually observed at
a) Low optical power densities
b) Medium optical power densities
c) High optical power densities
d) Threshold power densities

14. Stimulated Brillouin scattering is mainly a
a) Forward process
b) Backward process
c) Upward process
d) Downward process

15. Stimulated Raman scattering occur in
a) Forward direction
b) Backward direction
c) Upward direction
d) Forward and backward direction

16. Stimulated Raman scattering may have an optical power threshold of may be three orders of magnitude
a) Lower than Brillouin threshold
b) Higher than Brillouin threshold
c) Same as Brillouin threshold
d) Higher than Rayleigh threshold

17. What is dispersion in optical fiber communication?
a) Compression of light pulses
b) Broadening of transmitted light pulses along the channel
c) Overlapping of light pulses on compression
d) Absorption of light pulses

18. For no overlapping of light pulses down on an optical fiber link, the digital bit rate BT must be
a) Less than the reciprocal of broadened pulse duration
b) More than the reciprocal of broadened pulse duration
c) Same as that of than the reciprocal of broadened pulse duration
d) Negligible

19. What is pulse dispersion per unit length if for a graded index fiber, 0.1μs pulse broadening is seen over a distance of 13 km?
a) 6.12ns/km
b) 7.69ns/km
c) 10.29ns/km
d) 8.23ns/km

20. The optical source used in a fiber is an injection laser with a relative spectral width σλ/λ of 0.0011 at a wavelength of 0.70μm. Estimate the RMS spectral width.
a) 1.2 nm
b) 1.3 nm
c) 0.77 nm
d) 0.98 nm

21. Intermodal dispersion occurring in a large amount in multimode step index fiber results in
a) Propagation of the fiber
b) Propagating through the fiber
c) Pulse broadening at output
d) Attenuation of waves

22. Consider a single mode fiber having core refractive index n1= 1.5. The fiber length is 12m. Find the time taken by the axial ray to travel along the fiber.
a) 1.00μsec
b) 0.06μsec
c) 0.90μsec
d) 0.30μsec

23. A 4 km optical link consists of multimode step index fiber with core refractive index of 1.3 and a relative refractive index difference of 1%. Find the delay difference between the slowest and fastest modes at the fiber output.
a) 0.173 μsec
b) 0.152 μsec
c) 0.96 μsec
d) 0.121 μsec

24. The modal noise can be reduced by
a) Decreasing width of signal longitudinal mode
b) Increasing coherence time
c) Decreasing number of longitudinal modes
d) Using fiber with large numerical aperture

25. Disturbance along the fiber such as vibrations, discontinuities, connectors, splices, source/detectors coupling result in
a) Modal noise
b) Inter-symbol interference
c) Infrared interference
d) Pulse broadening

26. Practical pulse broadening value for graded index fiber lies in the range of
a) 0.9 to 1.2 ns/km
b) 0.2 to 1 ns/km
c) 0.23 to 5 ns/km
d) 0.45 to 8 ns/km

27. Dispersion-shifted single mode fibers are created by
a) Increasing fiber core diameter and decreasing fractional index difference
b) Decreasing fiber core diameter and decreasing fractional index difference
c) Decreasing fiber core diameter and increasing fractional index difference
d) Increasing fiber core diameter and increasing fractional index difference

28. he fibers which relax the spectral requirements for optical sources and allow flexible wavelength division multiplying are known as
a) Dispersion-flattened single mode fiber
b) Dispersion-enhanced single mode fiber
c) Dispersion-compressed single mode fiber
d) Dispersion-standardized single mode fiber

29. The variant of non-zero-dispersion-shifted fiber is called as
a) Dispersion flattened fiber
b) Zero-dispersion fiber
c) Positive-dispersion fiber
d) Negative-dispersion fiber

30. The optical source used for detection of optical signal is
a) IR sensors
b) Photodiodes
c) Zener diodes
d) Transistors

31. An optical fiber behaves as a birefringence medium due to differences in
a) Effective R-I and core geometry
b) Core-cladding symmetry
c) Transmission/propagation time of waves
d) Refractive indices of glass and silica

CONCLUSION

In this unit, the different kind of losses, signal distortion, Single mode fibers were discussed. The estimation of the losses and analyzing the propagation characteristics of an optical signal in different types of fibers were dealt in this unit.

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ASSIGNMENT

1. Explain the scattering and bending losses that occur in an optical fiber with relevant diagrams and expressions.
2. Write a brief note on design optimization of single mode fibers.
3. With diagram, explain intra and inter modal dispersion.
4. Discuss the attenuation encountered in optical fiber communication due to Bending, Scattering and Absorption.
5. What are the losses on signal attenuation mechanisms in a fiber? Explain in detail.
6. Discuss polarization mode dispersion and its limitations

AIM & OBJECTIVES

- To learn the basic elements of optical fiber transmission link, fiber modes configurations and structures.
- To understand the different kind of losses, signal distortion, SM fibers.
- To learn the various optical sources, materials and fiber splicing.
- To learn the fiber optical receivers and noise performance in photo detector.

PRE TEST-MCQ TYPE

1. How many types of sources of optical light are available?
a) One
b) Two
c) Three
d) Four

2. Which process gives the laser its special properties as an optical source?
a) Dispersion
b) Stimulated absorption
c) Spontaneous emission
d) Stimulated emission

3. A device which converts electrical energy in the form of a current into optical energy is called as
a) Optical source
b) Optical coupler
c) Optical isolator
d) Circulator

4. The majority of the carriers in a p-type semiconductor are __________
a) Holes
b) Electrons
c) Photons
d) Neutrons

5. The hole concentration in extrinsic materials is _________ electron concentration.
a) much greater than
b) lesser than
c) equal to
d) negligible difference with

UNIT III FIBER OPTICAL SOURCES AND COUPLING

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

THEORY

Introduction

Optical Sources:

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

Laser Diodes (LD)

Characteristics of Light Source of Communication

To be useful in an optical link, a light source needs the following characteristics It must be possible to operate the device continuously at a variety of temperatures for 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. The power requirement for its operation must be low. The light source must be compatible with the modern solid state devices. The optical output power must be directly modulated by varying the input current to the device. Better linearity of prevent harmonics and intermodulation distortion. High coupling efficiency. High optical output power. High reliability. Low weight and low cost.

Two types of light sources used in fiber optics are light emitting diodes (LEDs) and laser diodes (LDs).

Light Emitting Diodes (LEDs)

p-n Junction

Conventional p-n junction is called as homojunction as same semiconductor material is sued on both sides junction. The electron-hole recombination occurs in relatively layer = 10 μm. As the carriers are not confined to the immediate vicinity of junction, hence high current densities cannot 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 band gap discontinuity of the junction. Such a junction is called as heterojunction and the device is called double heterostructure.

In any optical communication system when the requirements is

1. Bit rate f 100-2—Mb/sec.

2. Optical power in tens of micro watts, LEDs are best suitable optical source.

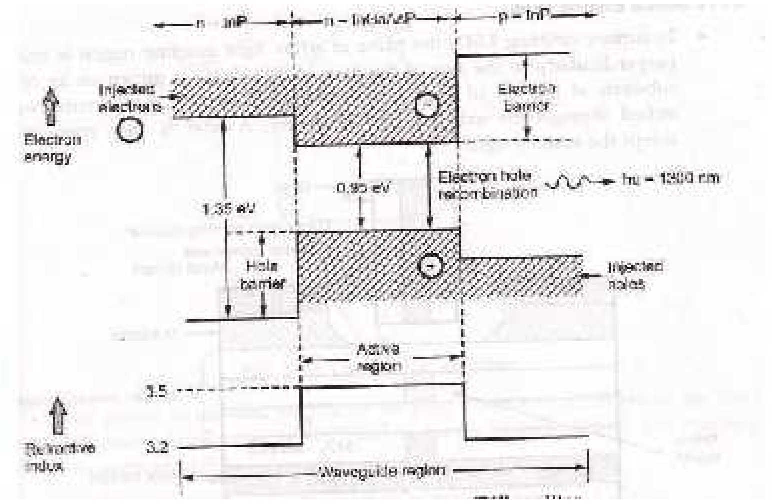
LED Structures

Heterojuncitons:

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

Double Heterojuncitons (DH):

In order to achieve efficient confinement of emitted radiation double heterojunction are used in LED structure. A heterojunction is a junction formed by dissimilar semiconductors. Double heterojunction (DH) is formed by two different semiconductors on each side of active region. Figure 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 for both 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 small active 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.

LED configurations

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

- ❖ Surface emitting LED
- ❖ Edge emitting LED.

Both devices used a DH structure to constrain the carriers and the light to an active layer.

Surface Emitting LEDs

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

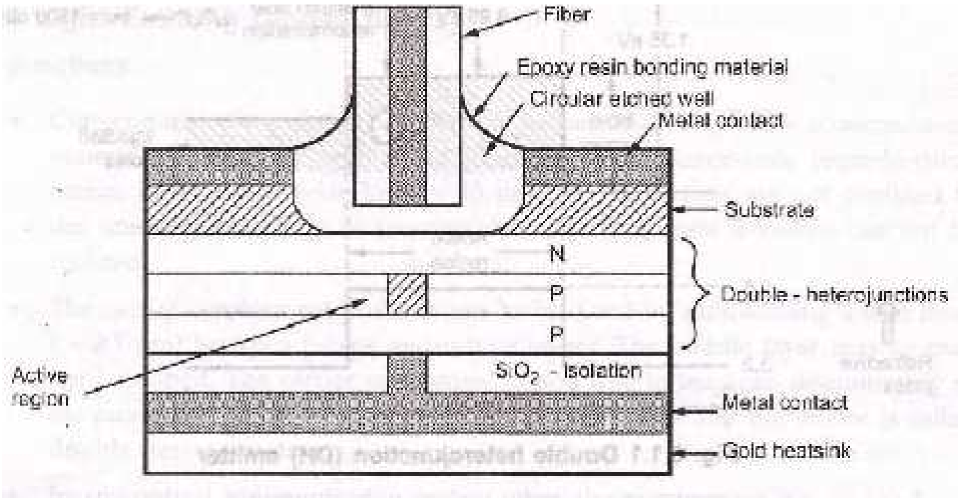


Figure Cross section through a typical surface emitting LED

At the back of device is a gold heat sink. The current flows through the p-type material and forms the small circular active region resulting in the intense beam of light.

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

The isotropic emission pattern from surface emitting LED is of Lambartian pattern. In Lambartian pattern, the emitting surface is uniformly bright, but its projected area diminishes as cos θ, where θ is the angle between the viewing direction and the normal to the surface as shown in Figure. The beam intensity is maximum along the normal.

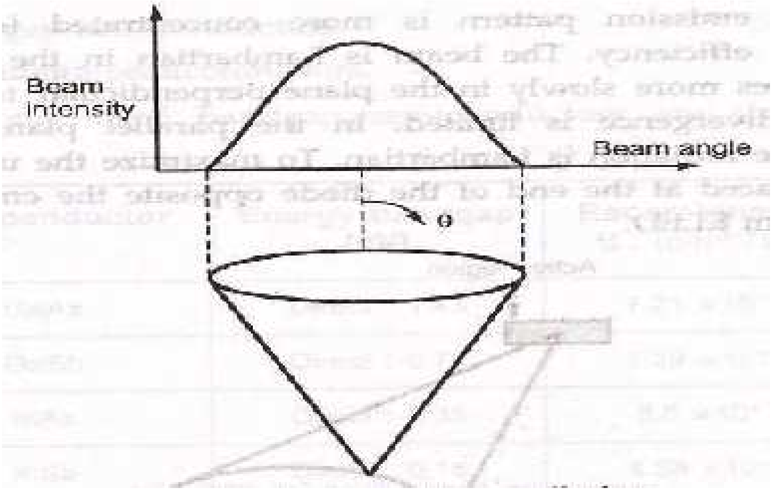


Figure Lambertian radiation

The power is reduced to 50% of its peak when θ = 60o, therefore the total half-power beamwidth is 120°. The radiation pattern decides the coupling efficiency of LED.

Edge Emitting LEDS (ELEDs)

In order to reduce the losses caused by absorption in the active layer and to make the beam more directional, the light is collected from the edge of the LED. Such a device is known as edge emitting LED or ELED. It consists of an active junction region which is the source of incoherent light and two guiding layers. The refractive index of guiding layers is lower than active region but higher than outer surrounding material. Thus a waveguide channel is form and optical radiation is directed into the fiber. Figure shows structure of LED

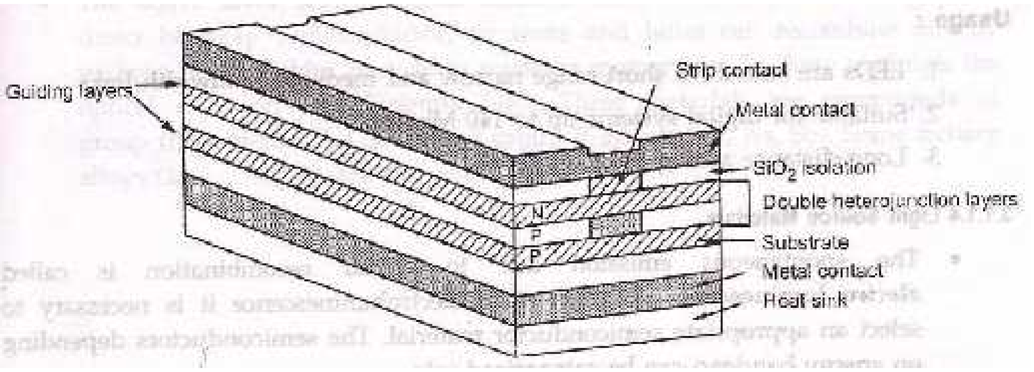


Figure Structure of Edge Emitting LED

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.

Features:

- Linear relationship between optical output and current.
- Spectral width is 25 to 400 nm for λ = 0.8 – 0.9 µm.

- Modulation bandwidth is much large.
- Not affected by catastrophic gradation mechanisms hence are more reliable.
- ELEDs have better coupling efficiency than surface emitter.
- ELEDs are temperature sensitive.

Usage:

1. LEDs are suited for short range narrow and medium bandwidth links.
2. Suitable for digital systems up to 140 Mb/sec.
3. Long distance analog links

Light Source Materials

The spontaneous emission due to carrier recombination is called electro luminescence. To encourage electroluminescence it is necessary to select as appropriate semiconductor material. The semiconductors depending on energy bandgap can be categorized into Direct bandgap semiconductors. Indirect bandgap semiconductors. Some commonly used bandgap semiconductors are shown in following table.

Direct bandgap semiconductors are most useful for this purpose. In direct bandgap semiconductors the electrons and holes on either side of bandgap have same value of crystal momentum. Hence direct recombination is possible. The recombination occurs within 10^{-8} to 10^{-10} sec. In indirect bandgap semiconductors, the maximum and minimum energies occur at different values of crystal momentum. The recombination in these semiconductors is quite slow 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.

Semiconductor	Energy bandgap (eV)	Recombination Br (cm3 s ec)
GaAs	Direct : 1.43	7.21 x 10-10
GaAs	Direct : 0.73	2.39 x 10-10
InAs	Direct : 0.35	8.5 x 10-11
InSb	Direct : 0.18	4.58 x 10-11
Si	Indirect : 1.12	1.79 x 10-15
Ge	Indirect : 0.67	5.25 x 10-14
GaP	Indirect : 2.26	5.37 x 10-14

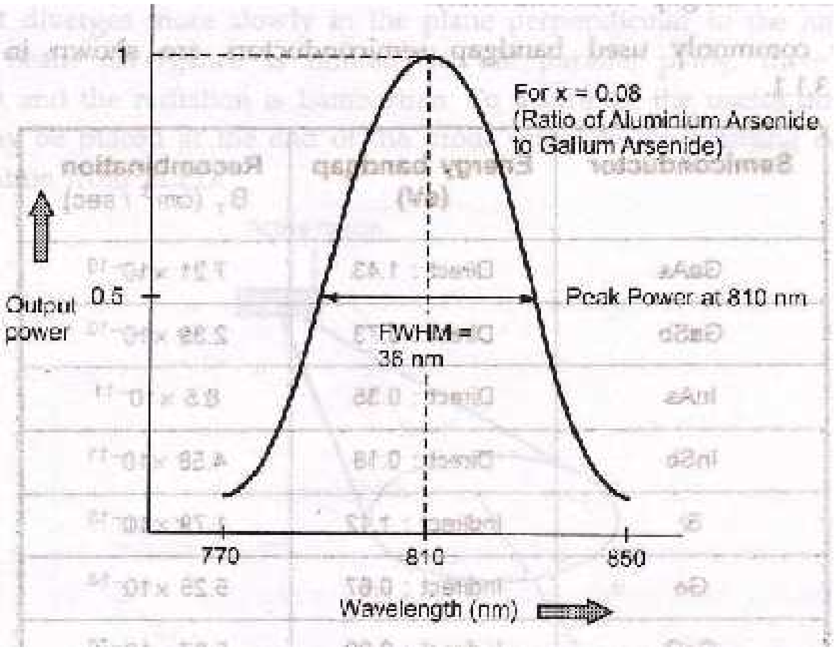


Figure Emission spectrum of Ga1-x AlxAs LED

The peak output power is obtained at 810 nm. The width of emission spectrum at half power (0.5) is referred as full width half maximum (FWHM) spectral width. For the given LED FWHM is 36 nm. The fundamental quantum mechanical relationship between gap energy E and frequency v is given as

$$E = hv$$

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

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

Where, energy (E) is in joules and wavelength (λ) is in meters. Expressing the gap energy (E_g) in electron volts and wavelength (λ) in micrometers for this application.

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

Different materials and alloys have different band gap energies. The bandgap energy (E_g) can be controlled by two compositional parameters x and y, within direct bandgap region. The quaternary alloy In1-x Gax Asy P1-y is the principal material sued in such LEDs. Two expression relating Eg and x,y are

$$\boxed{\mathbf{E_g = 1.424 + 1.266\,x + 0266\,x^2}}$$

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

Quantum Efficiency and Power

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

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

Where, R_r is radiative recombination rate.

R_{nr} is non-radiative recombination rate.

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

If n are the excess carriers, then radiative life time, and non-radiative life time,

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

The internal quantum efficiency is given and the recombination time of carriers in active region is τ

It is also known as bulk recombination life time.

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

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

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

Therefore internal quantum efficiency is given as

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

If the current injected into the LED is I and q is electron charge then total number of recombinations per second is

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

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

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

Optical power generated internally in LED is given as

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

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

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

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

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

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

The optical output power emitted from LED is given as

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

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

Bulk Recombination Life time (τ) :

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

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

Internal quantum efficiency (η_{int})

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

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

Internal power level (P_{int}) :

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

Advantages of LED

- Simple design.
- Ease of manufacture.
- Simple system integration.
- Low cost.
- High reliability.

Disadvantages of LED

- Refraction of light at semiconductor/air interface.
- The average life time of a radiative recombination is only a few nanoseconds, therefore
- Modulation BW is limited to only few hundred megahertz.
- Low coupling efficiency.
- Large chromatic dispersion.

Comparison of Surface and Edge Emitting LED

ED type	Max. modulation freq. (MHz)	Output power (mW)	Fiber coupled power
Surface emitting	60	< 4	< 0.2
Edge emitting	200	< 7	< 1.0

Injection Laser Diode (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 standing wave within a cavity (optical resonator) which provides an output of monochromatic highly coherent radiation.

Principle :

Material absorb light than emitting. Three different fundamental process occurs between the two energy states of an atom. 1) 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 x 10-34 J/s (Plank's constant).

An atom is initially in the lower energy state, when the photon with energy $(E_2 – E_1)$ is incident on the atom it will be excited into the higher energy state E_2 through the absorption of the photon

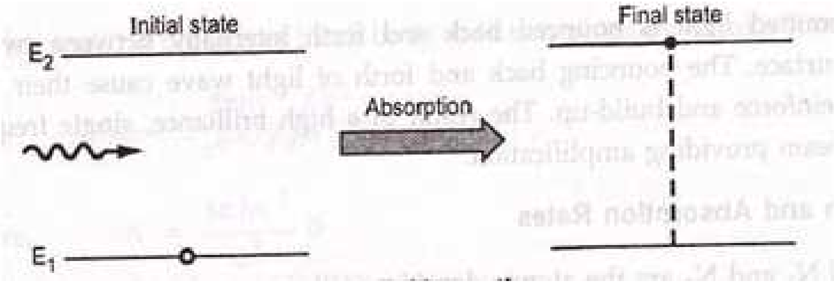


Figure Absorption

When the atom is initially in the higher energy state E_2, it can make a transition to the lower energy state E1 providing the emission of a photon at a frequency corresponding to E = 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 $(E_2 – E_1)$ interacts with the atom causing it to the lower state with the creation of the second photon.

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 back and forth internally between two reflecting surface. The bouncing back and forth of light wave cause their intensity to reinforce and build-up. The result in a high brilliance, single frequency light beam providing amplification.

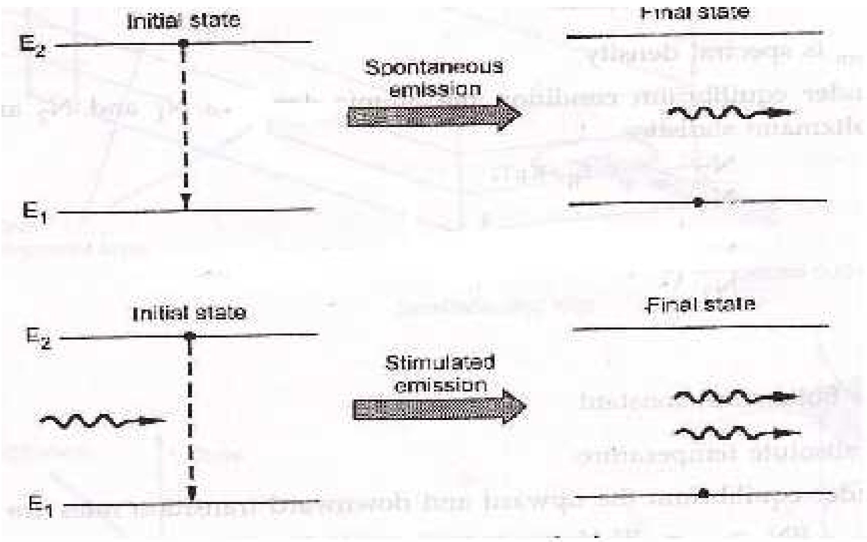


Figure Spontaneous and Stimulated emission

Emission and Absorption Rates

It N_1 and N_2 are the atomic densities in the ground and excited states.

Rate of spontaneous emission $R_{spon} = AN_2$

Rate of stimulated emission $R_{stim} = BN_2$ ρem **R**

ate of absorption Rabs = B’ N1 ρem

where, A, B and B’ are constants. ρem is spectral density. Under equilibrium condition the atomic densities N_1 and N_2 are given by Boltzmann statistics.

$$\frac{N_2}{N_1} = eg^{(-E_B / K_B T)}$$

$$\frac{N_2}{N_1} = eg^{(-h_v / K_B T)}$$

where, KB is Boltzmann constant.

T is absolute temperature.

Under equilibrium the upward and downward transition rates are equal.

$AN_2 + BN_2\ \rho em = B'\ N1\ \rho em$

Spectral density ρem

Comparing spectral density of black body radiation given by Plank's formula, 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,

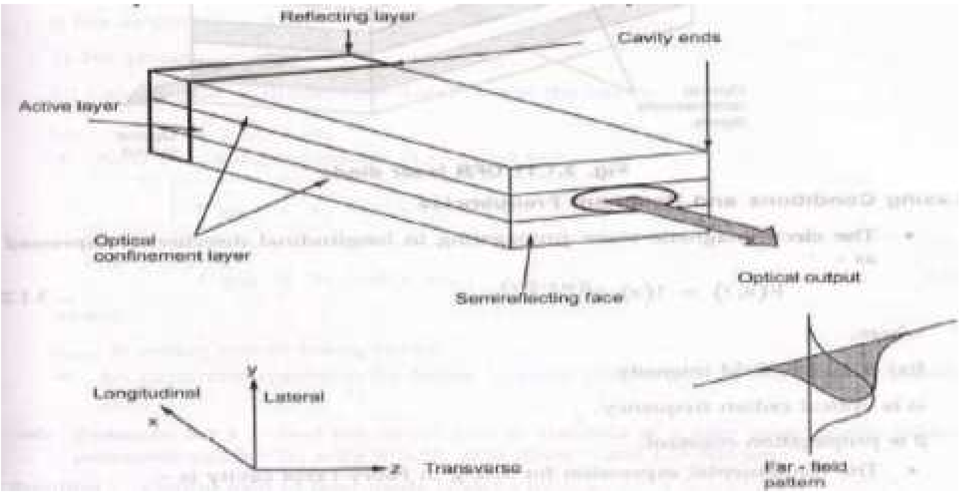


Figure Fabry –Perot Resonator

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. Figure shows Fabry-Perot resonator cavity for a laser diode. The two Heterojuncitons 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.

Distributed Feedback (DFB) Laser

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

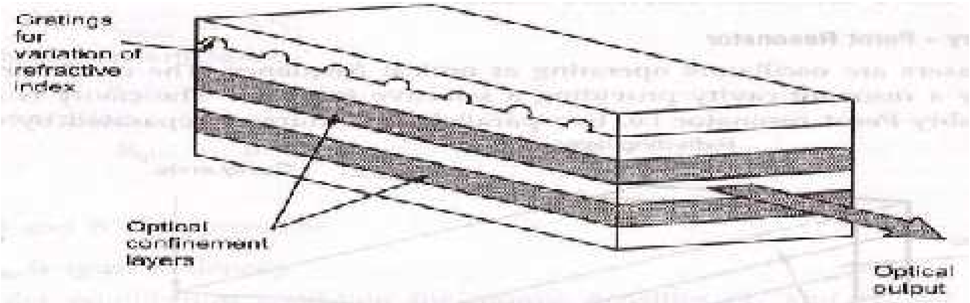


Figure DFB Laser Diode

Lasing conditions and resonant Frequencies

The electromagnetic wave propagating in longitudinal direction is expressed as – $E(z, t) = I(z)\ ej(\omega t-\beta z)$ where, $I(z)$ is optical field intensity. is optical radian frequency. β is propagation constant. The fundamental expression for lasing in Fabry-Perot cavity is

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

where, is optical field confinement factor or the fraction of optical power in the active layer.

α is effective absorption coefficient of material.

g is gain coefficient.

h v is photon energy.

z is distance traverses along the lasing cavity. The condition of lasing threshold is given as

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

For phase : $e^{-j2\beta L} = 1$

Optical gain at threshold = Total loss in the cavity.

i.e. $\Gamma\ g_{th} = \alpha_t$

Now the lasing expression is reduced to –

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

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

where, alpha end is mirror loss in lasing cavity. An important condition for lasing to occur is that gain, $g \geq g_{th}$ i.e. threshold gain.

Power Current Characteristics

The output optic power versus forward input current characteristics is plotted in Figure 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 (g_{th}) is related by threshold current density (J^{th}) for stimulated emission by expression $g_{th} = \beta$ where, β is constant for device structure

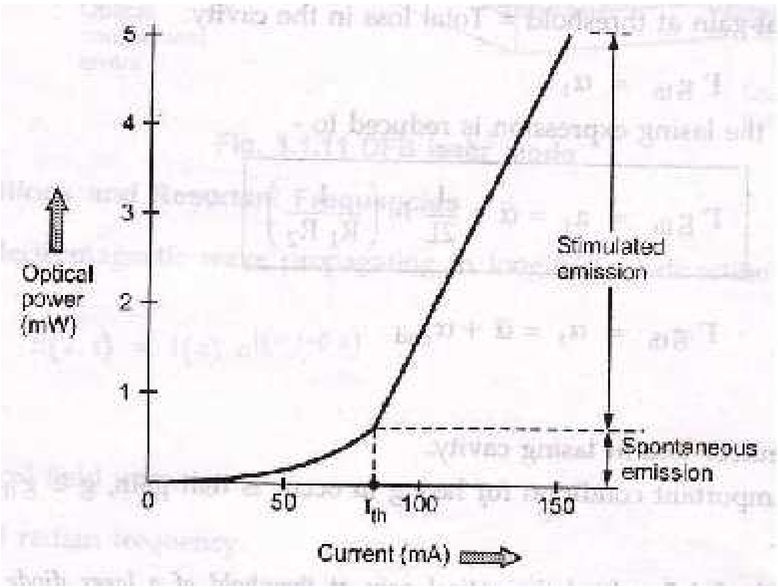


Figure Power Current Characteristics

Power current characteristics

External Quantum Efficiency

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

where,

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

η_i = Internal quantum efficiency (0.6-0.7). g_{th} = Threshold gain.

α = Absorption coefficient

Typical value of η_{ext} for standard semiconductor laser is ranging between 15-20 %.

Resonant Frequencies

At threshold lasing

$2\beta L = 2\pi m$

where, (propagation constant) m is an integer.

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

Since $c = v\lambda$

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

Substituting λ in above

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

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

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

where, g(0) is maximum gain. λ_0 is center wavelength in spectrum is spectral width of the gain. The frequency spacing between the two successive modes is

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

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

Advantages of Laser Diode

- Simple economic design.
- High optical power.
- Production of light can be precisely controlled.
- Can be used at high temperatures.
- Better modulation capability.
- High coupling efficiency.
- Low spectral width (3.5 nm)
- Ability to transmit optical output powers between 5 and 10 mW.
- Ability to maintain the intrinsic layer characteristics over long periods.

Disadvantages of Laser Diode

- At the end of fiber, a speckle pattern appears as two coherent light beams add or subtract their electric field depending upon their relative phases.
- Laser diode is extremely sensitive to overload currents and at high transmission rates, when laser is required to operate continuously the use of large drive current produces unfavourable thermal characteristics and necessitates the use of cooling and power stabilization.

Comparison of LED and Laser Diode

S. No.	Parameter	LED	LD (Laser Diode)
1	Principle of operation	Spontaneous emission.	Stimulated emission.
2	Output beam	Non – coherent	Coherent.
3	Spectral width	Board spectrum (20 nm – 100 nm)	Much narrower (1-5nm)
4	Data rate	Low.	Very high.
5	Transmission	Smaller.	Greater.
6	Temperature	Less sensitive.	More sensitive
7	Coupling efficiency	Very low.	High.
8	Compatible fibers	Multimode step index multimode	Single mode Sl
9	Circuit complexity	Simple	Complex
10	Life time	105 hours.	104 hours.
11	Cost	Low.	High.
12	Output power	Linearly proportional to	Proportional to current
13	Current required	Drive current 50 to 100 mA peak.	Threshold current 5 to
14	Applications	Moderate distance low data rate.	Long distance high data

Power Launching and coupling

Optical output of a luminescent source is usually measured by its radiance B at a given diode current.

Radiance: It is the optical power radiated into a unit solid angle per unit emitting surface area and is generally specified in terms of watts per square centimeter per steradian. Radiance = Power / per unit solid angle x per unit emitting surface area

Solid angle is defined by the projected area of a surface patch onto a unit sphere of a point. The angle that, seen from the center of a sphere, includes a given area on the surface of that sphere. The value of the solid angle is numerically equal to the size of that area divided by the square of the radius of the sphere.

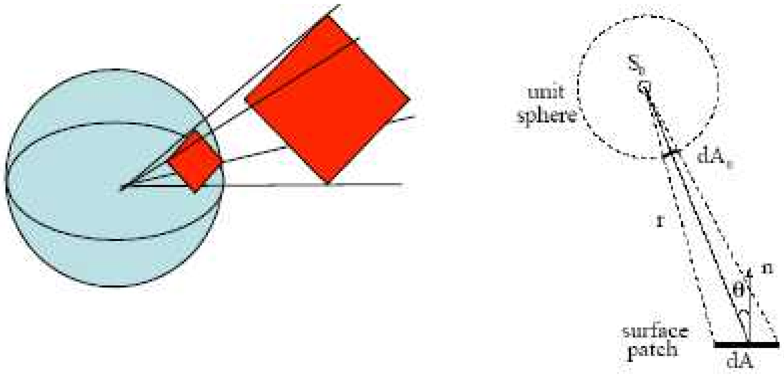


Figure Power launching

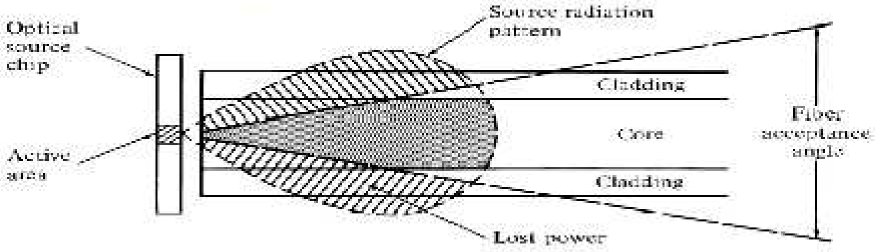


Figure Power coupled from source to fiber

Total power from LED to step index fiber

$$P_s = A_s \int_0^{2\pi} \int_0^{\pi/2} B(\theta, \phi) \sin\theta \, d\theta \, d\phi$$

$$\boxed{P_s = \pi r_s^{\,2} 2\pi B_0 \int_0^{\pi/2} \cos\theta \sin\theta \, d\theta = \pi^2 r_s^{\,2} B_0}$$

$$\boxed{P_{\mathrm{LED,step}} = \begin{Bmatrix} P_s (\mathrm{NA})^2 & \text{if } r_s < a \\ \left(\dfrac{a}{r_s}\right)^2 P_s (\mathrm{NA})^2 & \text{if } r_s \geq a \end{Bmatrix}}$$

Power coupled from the LED to the graded indexed fiber is given as

$$\boxed{\begin{aligned} P_{LED,gin} &= 2\pi^2 B_o \int_0^{r_s} \left[n^2(r) - n_2^2 \right] r\,dr ; n(r) = \mathrm{NA}(0)\sqrt{1 - (r/a)^\alpha} \\ &= 2P_s n_1^2 \Delta \left[1 - \frac{2}{\alpha + 2} \left(\frac{r_s}{a} \right)^\alpha \right] \end{aligned}}$$

If the medium between source and fiber is different from the core material with refractive index n, the power coupled into the fiber will be reduced by the factor

$$R = \left(\frac{n_1 - n}{n_1 + n} \right)^2$$

Lensing Scheme for Coupling Improvement

Several Possible lensing schemes are:

1. Rounded end fiber

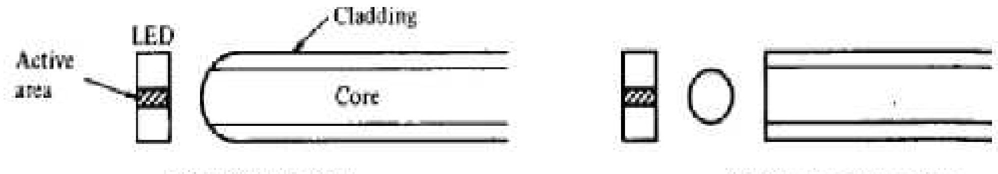
2. Nonimaging Microsphere (small glass sphere in contact with both the fiber and source)

3. Imaging sphere (a larger spherical lens used to image the source on the core area of the fiber end)

4. Cylindrical lens (generally formed from a short section of fiber)

5. Spherical surfaced LED and spherical ended fiber

6. Taper ended fiber.



Rounded-end fiber

Nonimaging microsphere

Imaging sphere

Cylindrical lens

Spherical-surfaced LED and spherical-ended fiber

Taper-ended fiber

Figure Examples of possible lensing scheme used to improve optical source to fiber coupling efficiency

Optical fiber connectors

An optical fiber connector terminates the end of an optical fiber, and enables quicker connection and disconnection than splicing. The connectors mechanically couple and align the cores of fibers so light can pass. Better connectors lose very little light due to reflection or 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 equipment or join two fiber connections without splicing. Hundreds of optical fiber connector 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 ends are optically smooth and the end-to-end positions are properly aligned.

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 material like 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

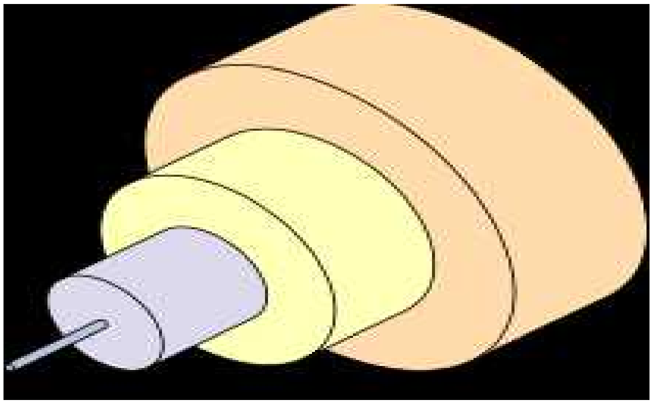
The fiber types for fiber optic connectors are categorized into simplex, duplex and multiple fiber connectors. A simplex connector has one fiber terminated in the connector, whereas duplex has two fibers terminated in the connector. Multiple fiber connectors can have two or more fibers terminated in 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.

Common optical fiber connectors include biconic, D4, ESCON, FC, FDDI, LC and SC.

- Biconic connectors use precision tapered ends to have low insertion loss.
- D4 connectors have a keyed body for easy intermateability.
- ESCON connectors are commonly used to connect from a wall outlet to a device.

- FC connector (fixed connection connector) is used for single-mode fibers and high-speed communication links.
- FDDI connector is a duplex connector which makes use of a fixed 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 and is best suited for high-density applications.

In fiber-optic communication, a single-mode optical fiber (SMF) is an optical fiber designed to carry only a single mode of light - the transverse mode. Modes are the possible solutions of the Helmholtz equation for waves, which is obtained by combining Maxwell's equations and 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 it 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 the length of the fiber, it is often called transverse mode since its electromagnetic oscillations occur perpendicular (transverse) to the length of the fiber.



The structure of a typical single-mode fiber.

1. Core 8 -9 µm diameter

2.Cladding 125 µm diameter

3.Buffer 250 µm diameter

4. Jacket 900 µm diameter

Like multi-mode optical fibers, single-mode fibers do exhibit modal dispersion resulting from multiple spatial modes but with narrower modal dispersion. 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 bandwidth than 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 circle is the cladding, 125 microns in diameter. Debris is visible as a streak on the cross- section, and glows due to the illumination.

A typical single-mode optical fiber has a core diameter between 8 and 10.5 µm and a cladding diameter of 125 µm. There are a number of special types of single-mode optical fiber which have been chemically or physically altered to give special properties, such as dispersion-shifted fiber and nonzero dispersion-shifted fiber. Data rates are limited by polarization 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 amplifiers and dispersion-compensating devices, state-of-the-art DWDM optical systems can span thousands of kilometers at 10 Gbit/s, and several hundred kilometers at 40 Gbit/s

The lowest-order bounds mode is ascertained for the wavelength of interest by solving Maxwell's equations for the boundary conditions imposed by the fiber, which are determined by the core diameter 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 than or equal to 2.405. For power-law profiles, single-mode operation occurs for a 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. The round circle is the cladding, 125 microns in diameter. Debris is visible as a streak on the cross- section, and glows due to the illumination.

In practice, the orthogonal polarizations may not be associated with degenerate modes.OS1 and OS2 are standard single-mode optical fiber used with wavelengths 1310 nm and 1550 nm (size 9/125 µm) with a maximum attenuation of 1 dB/km (OS1) and 0.4 dB/km (OS2). OS1 is defined in ISO/IEC 11801 and OS2 is defined in ISO/IEC 24702.

Optical fiber 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 of an adapter and two connector plugs. Due to the sophisticated polishing and tuning 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.

Optical fiber connectors are used in telephone company central offices, at installations on customer premises, and in outside plant applications. Their uses include:

- Making the connection between equipment and the telephone plant in the central office
- Connecting fibers to remote and outside plant electronics such as Optical Network Units (ONUs) and Digital Loop Carrier (DLC) systems
- Optical cross connects in the central office
- Patching panels in the outside plant to provide architectural flexibility and to interconnect fibers belonging to different service providers

- Connecting couplers, splitters, and Wavelength Division Multiplexers (WDMs) to optical fibers
- Connecting optical test equipment to fibers for testing and maintenance.

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 will prevent the connectors within being subjected to temperature swings unless 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 in Telcordia GR-326, Generic Requirements for Single mode Optical Connectors and Jumper Assemblies. A multi-fiber optical connector is designed to simultaneously join multiple optical fibers together, with each optical 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.

The latter joins one optical fiber to two or more other optical fibers. 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’ Central Offices (COs), installations on customer premises, and Outside Plant (OSP) applications. The multi-fiber optical connector can be used in the creation of a low-cost switch 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 R_L is a measure of the portion of light that is reflected back to the source at the junction. It is expressed in decibel. The higher the RL value in decibels, the lower is the reflections. Typical R_L 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 end faces were polished to an angle of 90° to the 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 I_L and R_L values identical to 8° versions, and for this reason they have not established themselves worldwide.

Return Loss

In optics (particularly in fiber optics) a loss that takes place at discontinuities of refractive index, especially at an air-glass interface such as a fiber end face. At those interfaces, a fraction of the optical signal is reflected back toward the source. This reflection phenomenon is also called "Fresnel reflection loss," or simply "Fresnel loss."

Fiber optic transmission systems use lasers to transmit signals over optical fiber, and a high optical return loss (ORL) can cause the laser to stop transmitting correctly. The measurement of ORL is becoming more important in the characterization of optical networks as the use of wavelength-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.

Definition of Return 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.

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

where P_{out} is the reflected power and P_{in} is the incident, or input, power.
Sources of loss include reflections and scattering along the fiber network. A typical R_L value for an Angled Physical Contact (APC) connector is about -55dB, while the R_L from an open flat polish to air is typically about -14dB. High R_L is a large concern in high bit rate digital or analog single mode systems and is also an indication of a potential failure point, or compromise, in any optical network.

Fiber alignment and joint loss

A major consideration with all types of fiber–fiber connection is the optical loss encountered at the interface. Even when the two jointed fiber ends are smooth and perpendicular to the fiber axes, and the two fiber axes are perfectly aligned, a small proportion of the light may be reflected back into the transmitting fiber causing attenuation at the joint. This phenomenon, known as Fresnel reflection,

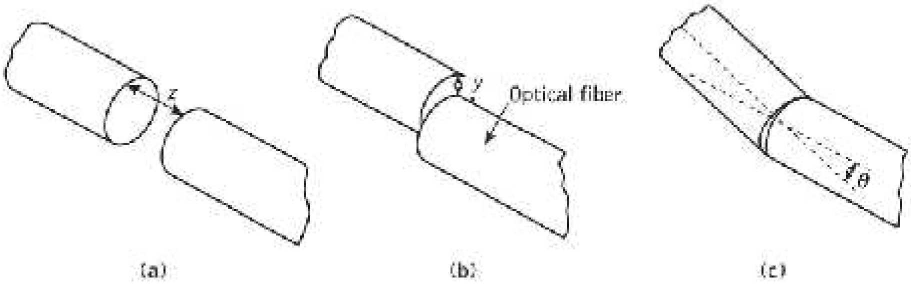


Figure the three possible types of misalignment which may occur when jointing compatible optical fibers: (a) longitudinal misalignment; (b) lateral misalignment; (c) angular misalignment

It is apparent that Fresnel reflection may give a significant loss at a fiber joint even when all other aspects of the connection are ideal. However, the effect of Fresnel reflection at a fiber–fiber connection can be reduced to a very low level through the use of an index-matching fluid in the gap between the jointed fibers. When the index-matching fluid has the same refractive index as the fiber core, losses due to Fresnel reflection are in theory eradicated.

Unfortunately, Fresnel reflection is only one possible source of optical loss at a fiber joint. A potentially greater source of loss at a fiber–fiber connection is caused by misalignment of the two jointed fibers. In order to appreciate the development and relative success of various connection techniques it is useful to discuss fiber alignment in greater detail.

Any deviations in the geometrical and optical parameters of the two optical fibers which are jointed will affect the optical attenuation (insertion loss) through the connection. It is not possible within any particular connection technique to allow for all these variations. Hence, there are inherent connection problems when jointing fibers with, for instance

- ✓ different core and/or cladding diameters;
- ✓ different numerical apertures and/or relative refractive index differences;
- ✓ different refractive index profiles;
- ✓ fiber faults (core ellipticity, core concentricity, etc.).

The losses caused by the above factors together with those of Fresnel reflection are usually referred to as intrinsic joint losses. The best results are therefore achieved with compatible (same)

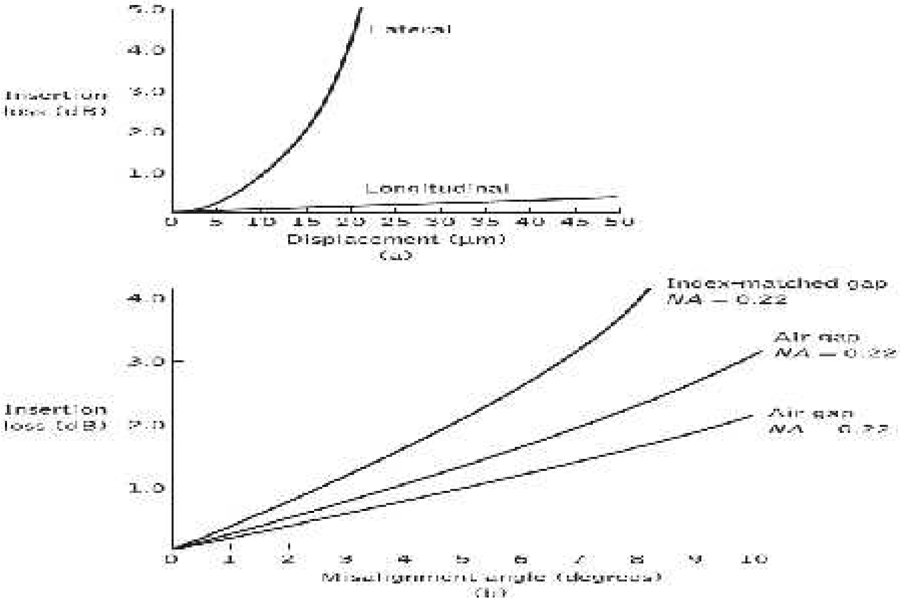


Figure Insertion loss characteristics for jointed optical fibers with various types of misalignment: (a) insertion loss due to lateral and longitudinal misalignment for a graded index fiber of 50 µm core diameter.

In this case there is still the problem of the quality of the fiber alignment provided by the jointing mechanism. Examples of possible misalignment between coupled compatible optical fibers are illustrated in Figure. It is apparent that misalignment may occur in three dimensions: the separation between the fibers (longitudinal misalignment), the offset perpendicular to the fiber core axes (lateral/radial/ axial misalignment) and the angle between the core axes (angular misalignment). Optical losses resulting from these three types of misalignment depend upon the fiber type, core diameter and the distribution of the optical power between the propagating modes.

Examples of the measured optical losses due to the various types of misalignment are shown in Figure and shows the attenuation characteristic for both longitudinal and lateral misalignment of a graded index fiber of 50 µm core diameter.

It may be observed that the lateral misalignment gives significantly greater losses per unit displacement than the longitudinal misalignment. For instance, in this case a lateral displacement of 10 µm gives about 1 dB insertion loss whereas a similar longitudinal displacement gives an insertion loss of around 0.1 dB. Figure shows the attenuation characteristic for the angular misalignment of two multimode step index fibers with numerical apertures of 0.22 and 0.3. An insertion loss of around 1 dB is obtained with angular misalignment of 4° and 5° for the NA =0.22 and NA =0.3 fibers respectively It may also be observed in figure that the effect of an index-matching fluid in the fiber gap causes increased losses with angular misalignment. Therefore, it is clear that relatively small levels of lateral and/or angular misalignment can cause significant attenuation at a fiber joint. This is especially the case for fibers of small core diameter (less than 150 µm) which are currently employed for most telecommunication purposes.

Multimode fiber joints

Theoretical and experimental studies of fiber misalignment in optical fiber connections allow approximate determination of the losses encountered with the various misalignments of different fiber types. Here some of the expressions used to calculate losses due to lateral and angular misalignment of optical fiber joints. Longitudinal misalignment is not discussed in detail as it tends to be the least important effect and may be largely avoided in fiber connection. Both groups of workers claim good agreement with experimental results, which is perhaps understandable when considering the number of variables involved in the measurement. Also, all groups predict higher losses for fibers with larger numerical apertures, which is consistent with intuitive considerations (i.e. the larger the numerical aperture, the greater the spread of the output light and the higher the optical loss at a longitudinally misaligned joint).

Theoretical expressions for the determination of lateral and angular misalignment losses are by no means definitive, although in all cases they claim reasonable agreement with experimental results. However, experimental results from different sources tend to vary (especially for angular misalignment losses) due to difficulties of measurement. It is therefore not implied that the expressions given in the text are necessarily the most accurate, as at present the choice appears somewhat arbitrary. Lateral misalignment reduces the overlap region between the two fiber cores. Assuming uniform excitation of all the optical modes in a multimode step index fiber, the overlapped area between both fiber cores approximately gives the lateral coupling efficiency µlat. Hence, the lateral coupling efficiency for two similar step index fibers may be written as

$$\eta_{\text{lat}} \simeq \frac{16(n_1/n)^2}{[1+(n_1/n)]^4}\frac{1}{\pi}\left\{2\cos^{-1}\left(\frac{y}{2a}\right)-\left(\frac{y}{a}\right)\left[1-\left(\frac{y}{2a}\right)^2\right]^{\frac{1}{2}}\right\}$$

where n_1 is the core refractive index, n is the refractive index of the medium between the fibers, y is the lateral offset of the fiber core axes, and a is the fiber core radius. The lateral misalignment loss in decibels may be determined using:

$$\text{Loss}_{\text{lat}} = -10\log_{10}\eta_{\text{lat}}\ \text{dB}$$

The predicted losses obtained using the formulas given are generally slightly higher than the measured values due to the assumption that all modes are equally excited. This assumption is only correct for certain cases of optical fiber transmission. Also, certain authors assume index matching and hence no Fresnel reflection, which makes the first term in equation equal to unity (as $n_1/n = 1$). This may be valid if the two fiber ends are assumed to be in close contact (i.e. no air gap in between) and gives lower predicted losses. Nevertheless, bearing in mind these possible inconsistencies, useful estimates for the attenuation due to lateral misalignment of multimode step index fibers may be obtained. Lateral misalignment loss in multimode graded index fibers assuming a uniform distribution of optical power throughout all guided modes was calculated by Gloge. He estimated that the lateral misalignment loss was dependent on the refractive index gradient α for small lateral offset and may be obtained from:

$$L_t = \frac{2}{\pi}\left(\frac{y}{a}\right)\left(\frac{\alpha+2}{\alpha+1}\right) \quad \text{for } 0 \leq y \leq 0.2a$$

Where the lateral coupling efficiency was given by:

$$\eta_{\text{lat}} = 1 - L_t$$

Hence it may be utilized to obtain the lateral misalignment loss in decibels. With a parabolic refractive index profile where α = 2, gives: A further estimate including the leaky modes gave a revised expression for the lateral misalignment loss given in Equation of 0.75(y/a). This analysis was also extended to step index fibers (where α = ∞) and gave lateral misalignment losses of 0.64(y/a) and 0.5(y/a) for the cases of guided modes only and both guided plus leaky modes respectively.

Factors causing fiber–fiber intrinsic losses were listed in previous Section; the major ones comprising a mismatch in the fiber core diameters, a mismatch in the fiber numerical apertures and differing fiber refractive index profiles are illustrated in Figure. Connections between multimode fibers with certain of these parameters being different can be quite common, particularly when a pigtailed optical source is used, the fiber pigtail of which has different characteristics from the main transmission fiber. Moreover, as indicated previously, diameter variations can occur with the same fiber type. Assuming all the modes are equally excited in a multimode step or graded index fiber, and that the numerical apertures and index profiles are the same, then the loss resulting from a mismatch of core diameters is given by:

$$\text{Loss}_{\text{CD}} = \begin{cases} -10\log_{10}\left(\frac{a_2}{a_1}\right)^2 \ (\text{dB}) & a_2 < a_1 \\ 0 \qquad\qquad\qquad\quad (\text{dB}) & a_2 \geq a_1 \end{cases}$$

where $a1$ and $a2$ are the core radii of the transmitting and receiving fibers respectively. It may be observed from Equation that no loss is incurred if the receiving fiber has a larger core diameter than the transmitting one. In addition, only a relatively small loss (0.09 dB) is obtained when the receiving fiber core diameter is 1% smaller than that of the transmitting fiber. When the transmitting fiber has a higher numerical aperture than the receiving fiber, then some of the emitted light rays will fall outside the acceptance angle of the receiving fiber and they will therefore not be coupled through the joint.

Again assuming a uniform modal power distribution, and fibers with equivalent refractive index profiles and core diameters, then the loss caused by a mismatch of numerical apertures

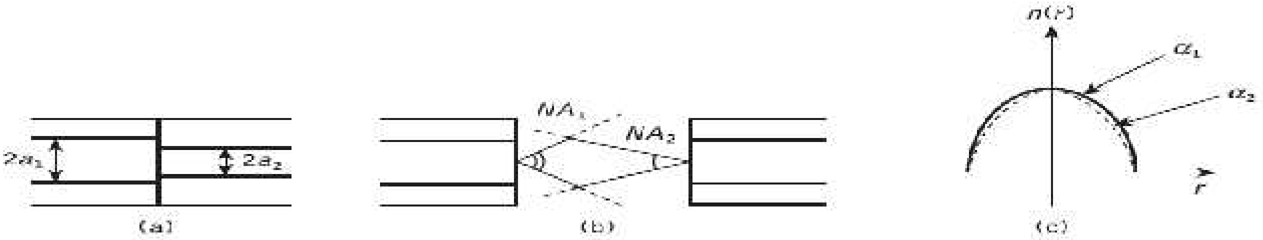


Figure Some intrinsic coupling losses at fiber joints: (a) core diameter mismatch; (b) numerical aperture mismatch; (c) refractive index profile difference

$$\text{Loss}_{\text{NA}} = \begin{cases} -10\log_{10}\left(\frac{NA_2}{NA_1}\right)^2 \text{ (dB)} & NA_2 < NA_1 \\ 0 \text{ (dB)} & NA_2 \geq NA_1 \end{cases}$$

$$\text{Loss}_{\text{RI}} = \begin{cases} -10\log_{10}\frac{\alpha_2(\alpha_1+2)}{\alpha_1(\alpha_2+2)} \text{ (dB)} & \alpha_2 < \alpha_1 \\ 0 \text{ (dB)} & \alpha_2 \geq \alpha_1 \end{cases}$$

$$\text{Loss}_{\text{int}} = \begin{cases} -10\log_{10}\frac{(a_2 NA_2)^2(\alpha_1+2)\alpha_2}{(a_1 NA_1)^2(\alpha_2+2)\alpha_1} \text{ (dB)} & a_2 > a_1,\ NA_2 > NA_1,\ \alpha_2 > \alpha_1 \\ 0 \text{ (dB)} & a_2 \leq a_1,\ NA_2 \leq NA_1,\ \alpha_2 \leq \alpha_1 \end{cases}$$

Single-mode fiber joints

Misalignment losses at connections in single-mode fibers have been theoretically considered by Marcuse and Gambling. The theoretical analysis which was instigated by Marcuse is based upon the Gaussian or near-Gaussian shape of the modes propagating in single-mode fibers regardless of the fiber type (i.e. step index or graded index). Further development of this theory by Gambling *et al.* gave simplified formulas for both the lateral and angular misalignment losses at joints in single mode fibers. In the absence of angular misalignment Gambling *et al.* calculated that the loss T_l due to lateral offset y was given by:

$$T_l = 2.17\left(\frac{y}{\omega}\right)^2 \text{dB}$$

Where ω is the normalized spot size of the fundamental mode. However, the normalized spot size for the LP01 mode (which corresponds to the HE mode) may be obtained from the empirical formula:

$$\omega = a\frac{(0.65 + 1.62V^{\frac{3}{2}} + 2.88V^{-6})}{2^{\frac{1}{2}}}$$

where ω is the spot size in μm, *a* is the fiber core radius and *V* is the normalized frequency for the fiber. Alternatively, the insertion loss T_a caused by an angular misalignment θ (in radians) at a joint in a single-mode fiber may be given by

$$T_a = 2.17\left(\frac{\theta\omega\, n_1 V}{aNA}\right)^2 \text{dB}$$

where n_1 is the fiber core refractive index and *NA* is the numerical aperture of the fiber. It must be noted that the formulas given in assume that the spot sizes of the modes in the two coupled fibers are the same. Gambling *et al.* also derived a somewhat complicated formula which gave a good approximation for the combined losses due to both lateral and angular misalignment at a fiber joint. However, they indicate that for small total losses (less than 0.75 dB) a reasonable approximation is obtained by simply combining Assuming that no losses are present due to the extrinsic factors, the intrinsic coupling loss is given by where ω_{01} and ω_{02} are the spot sizes of the transmitting and receiving fibers respectively. Equation therefore enables the additional coupling loss resulting from mode-field diameter mismatch between two single-mode fibers to be calculated.

Fiber splices

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

Fusion splicing is accomplished by applying localized heating (e.g. by a flame or an electric arc) at the interface between two butted, prealigned fiber ends causing them to soften and fuse. Mechanical splicing, in which the fibers are held in alignment by some mechanical means, may be achieved by various methods including the use of tubes around the fiber ends (tube splices) or V-grooves into which the butted fibers are placed (groove splices). All these techniques seek to optimize the splice performance (i.e. reduce the insertion loss at the joint) through both fiber end preparation and alignment of the two joint fibers.

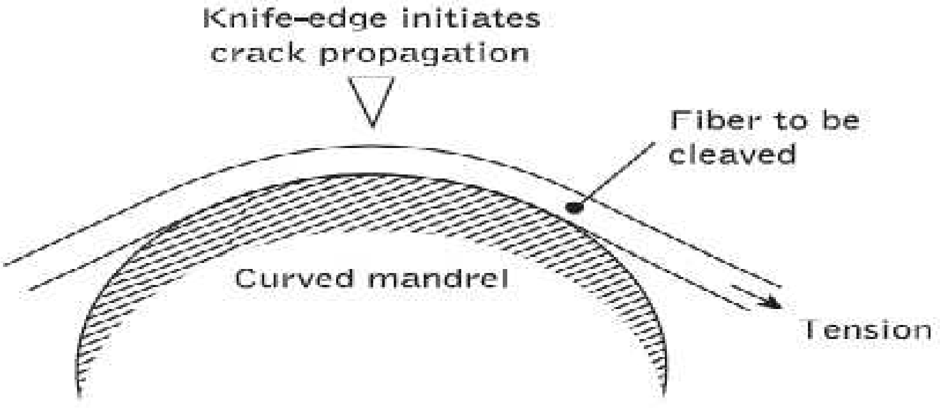


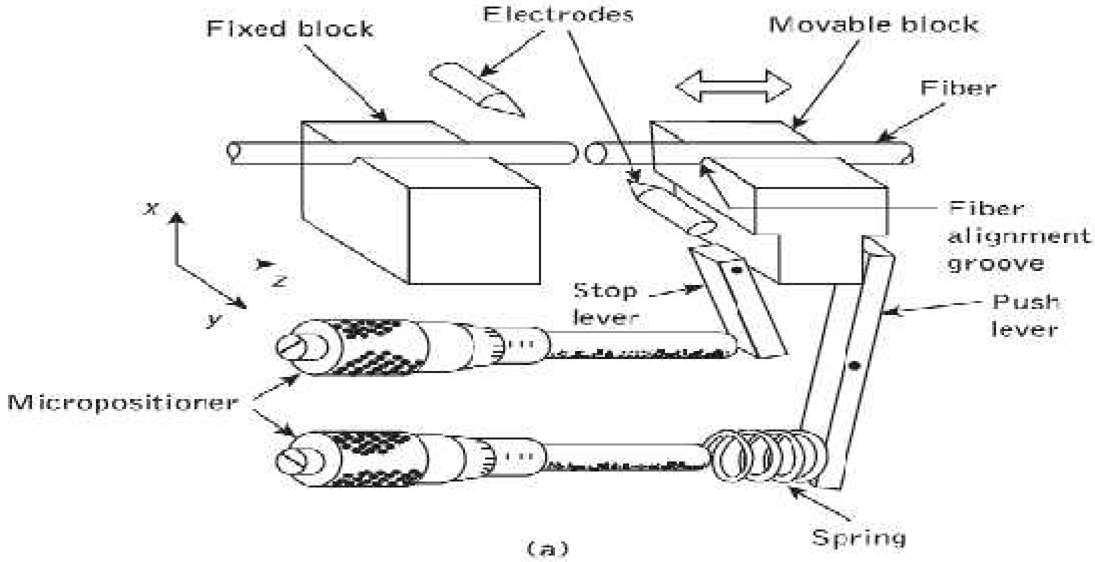
Figure Optical fiber end preparation: the principle of scribe and break cutting

Typical average splice insertion losses for multimode fibers are in the range 0.1 to 0.2 dB which is generally a better performance than that exhibited by demountable connections. It may be noted that the insertion losses of fiber splices are generally much less than the possible Fresnel reflection loss at a butted fiber–fiber joint. This is because there is no large step change in refractive index with the fusion splice as it forms a continuous fiber connection, and some method of index matching (e.g. a fluid) tends to be utilized with mechanical splices.

A requirement with fibers intended for splicing is that they have smooth and square end faces. In general this end preparation may be achieved using a suitable tool which cleaves the fiber as illustrated in Figure. This process is often referred to as scribe and break or score and break as it involves the scoring of the fiber surface under tension with a cutting tool (e.g. sapphire, diamond, tungsten carbide blade). The surface scoring creates failure as the fiber is tensioned and a clean, reasonably square fiber end can be produced. Figure illustrates this process with the fiber tensioned around a curved mandrel. However, straight pull, scribe and break tools are also utilized, which arguably give better results.

Fusion splices

The fusion splicing of single fibers involves the heating of the two prepared fiber ends to their fusing point with the application of sufficient axial pressure between the two optical fibers. It is therefore essential that the stripped (of cabling and buffer coating) fiber ends are adequately positioned and aligned in order to achieve good continuity of the transmission medium at the junction point. Hence the fibers are usually positioned and clamped with the aid of an inspection microscope. Flame heating sources such as microplasma torches (argon and hydrogen) and oxhydric microburners (oxygen, hydrogen and alcohol vapor) have been utilized with some success. However, the most widely used heating source is an electric arc. This technique offers advantages of consistent, easily controlled heat with adaptability for use under field conditions. which involves the rounding of the fiber ends with a low-energy discharge before pressing the fibers together and fusing with a stronger arc. This technique, known as prefusion, removes the requirement for fiber end preparation which has a distinct advantage in the field environment. It has been utilized with multimode fibers giving average splice losses of 0.09 db.



(a)

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

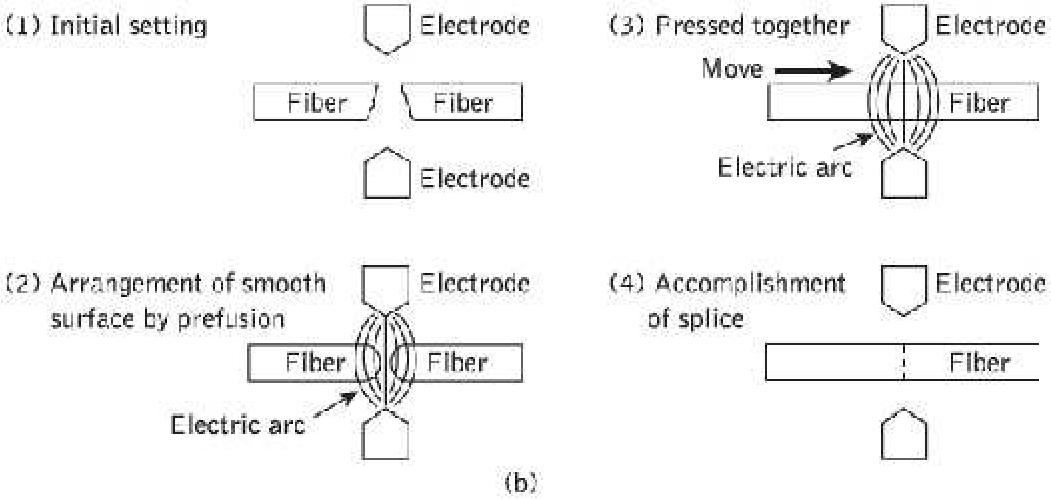


Figure Electric arc fusion splicing: (a) an example of fusion splicing apparatus; (b) schematic illustration of the prefusion method for accurately splicing optical fibers

Self-alignment, illustrated in Figure, is caused by surface tension effects between the two fiber ends during fusing. An early field trial of single-mode fiber fusion splicing over a 31.6 km link gave mean splice insertion losses of 0.18 and 0.12 dB at wavelengths of 1.3 and 1.55 µm respectively. Mean splice losses of only 0.06 dB have also been obtained with a fully automatic single-mode fiber fusion splicing machine weaken the fiber in the vicinity of the splice. It has been found that even with careful handling, the tensile strength of the fused fiber may be as low as 30% of that of the uncoated fiber before fusion.

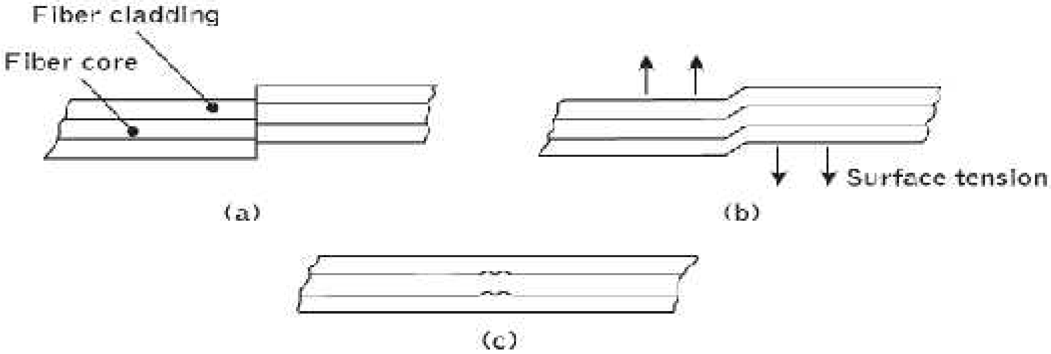


Figure Self-alignment phenomenon which takes place during fusion splicing: (a) before fusion; (b) during fusion; (c) after fusion

The fiber fracture generally occurs in the heat affected zone adjacent to the fused joint. The reduced tensile strength is attributed to the combined effects of surface damage caused by handling, surface defect growth during heating and induced residential stresses due to changes in chemical composition. It is therefore necessary that the completed splice is packaged so as to reduce tensile loading upon the fiber in the vicinity of the splice.

Mechanical splices

A number of mechanical techniques for splicing individual optical fibers have been developed. A common method involves the use of an accurately produced rigid alignment tube into which the prepared fiber ends are permanently bonded. This snug tube splice is illustrated in Figure and may utilize a glass or ceramic capillary with an inner diameter just large enough to accept the optical fibers. Transparent adhesive (e.g. epoxy resin) is injected through a transverse bore in the capillary to give mechanical sealing and index matching of the splice. Average insertion losses as low as 0.1 dB have been obtained with multimode graded index and single-mode fibers using ceramic capillaries. However, in general, snug tube splices exhibit problems with capillary tolerance requirements. Hence as a commercial product they may exhibit losses of up to 0.5 dB.

Mechanical splicing technique which avoids the critical tolerance requirements of the snug tube splice is shown in Figure. This loose tube splice uses an oversized square-section metal tube which easily accepts the prepared fiber ends. Transparent adhesive is first inserted into the tube followed by the fibers. The splice is self-aligning when the fibers are curved in the same plane, forcing the fiber ends simultaneously into the same corner of the tube, as indicated in Figure. Mean splice insertion losses of 0.073 dB have been achieved using multimode graded index fibers with the loose tube approach.

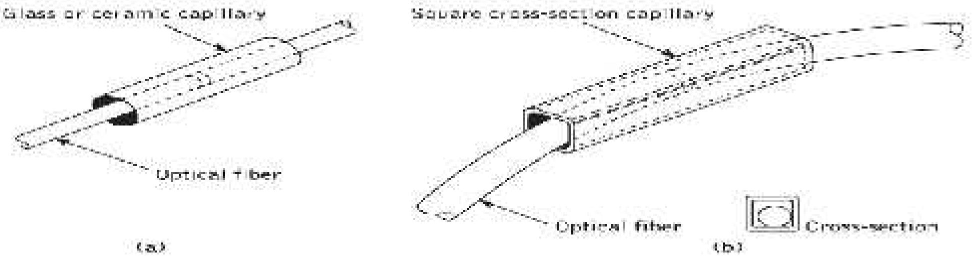


Figure Techniques for tube splicing of optical fibers: (a) snug tube splice; (b) loose tube splice utilizing square cross-section capillary

Other common mechanical splicing techniques involve the use of grooves to secure the fibers to be jointed. A simple method utilizes a V-groove into which the two prepared fiber ends are pressed. The V-groove splice which is illustrated in Figure gives alignment of the prepared fiber ends through insertion in the groove. The splice is made permanent by securing the fibers in the V-groove with epoxy resin. Jigs for producing Vgroove splices have proved quite successful, giving joint insertion losses of around 0.1 dB.

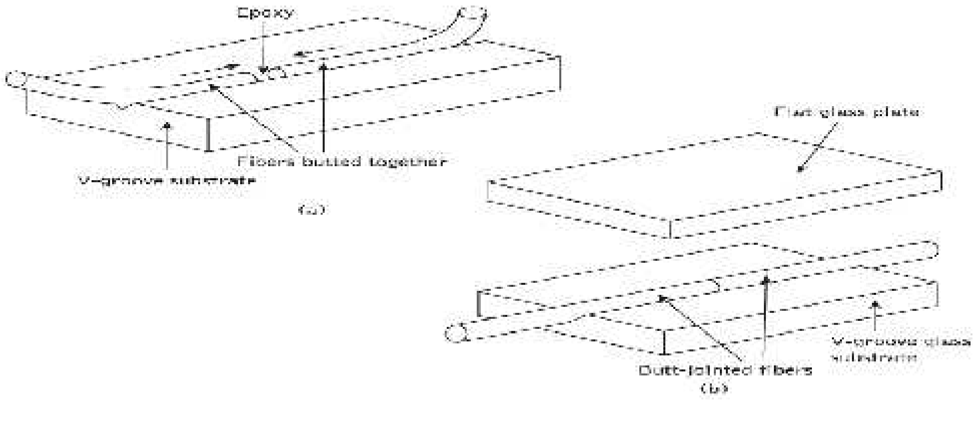


Figure V-groove splices

V-groove splices formed by sandwiching the butted fiber ends between a V-groove glass substrate a flat glass retainer plate, as shown in Figure, have also proved very successful in the laboratory. Splice insertion losses of less than 0.01 dB when coupling single-mode fibers have been reported using this technique. However, reservations are expressed regarding the field implementation of these splices with respect to manufactured fiber geometry, and housing of the splice in order to avoid additional losses due to local fiber bending.

A further variant on the V-groove technique is the elastic tube or elastomeric splice shown. The device comprises two elastomeric internal parts, one of which contains a V-groove. An outer sleeve holds the two elastic parts in compression to ensure alignment of the fibers in the V-groove, and fibers with different diameters tend to be centered and hence may be successfully spliced. Although originally intended for multimode fiber connection, the device has become a widely used commercial product which is employed with single-mode fibers, albeit often as a temporary splice for laboratory investigations. The splice loss for the elastic tube device was originally reported as 0.12 dB or less but is generally specified as around 0.25 dB for the commercial product. In addition, index-matching gel is normally employed within the device to improve its performance.

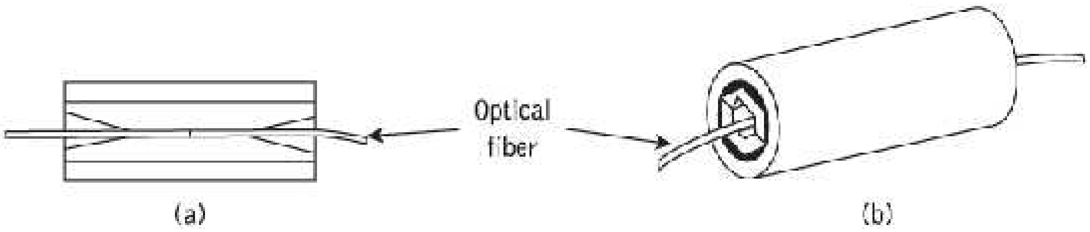


Figure The elastomeric splice: (a) cross-section; (b) assembly

A slightly more complex groove splice known as the Springroove splice utilized a bracket containing two cylindrical pins which serve as an alignment guide for the two prepared fiber ends. The cylindrical pin diameter was chosen to allow the fibers to protrude above the cylinders, as shown in Figure. An elastic element (a spring) was used to press the fibers into a groove and maintain the fiber end alignment, as illustrated in Figure. The complete assembly was secured using a drop of epoxy resin. Mean splice insertion losses of 0.05 dB were obtained using multimode graded index fibers with the Springroove splice. This device found practical use in Italy.

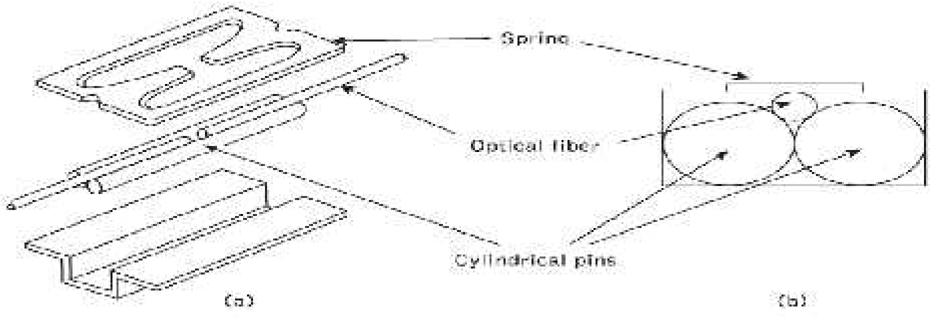
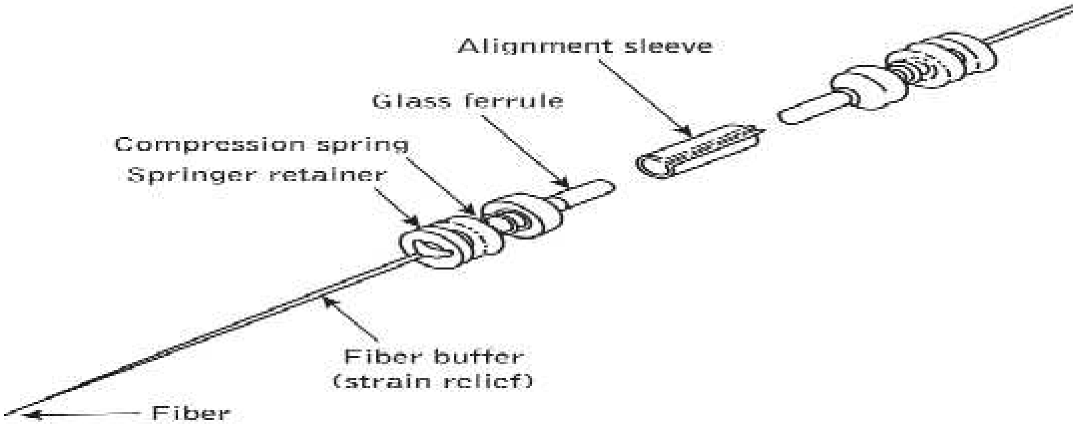


Figure the Springroove splice: (a) expanded overview of the splice; (b) schematic cross-section of the splice

An example of a secondary aligned mechanical splice for multimode fiber is shown in Figure. This device uses precision glass capillary tubes called ferrules as the secondary elements with an alignment sleeve of metal or plastic into which the glass tubed fibers are inserted. Normal assembly of the splice using 50 µm core diameter fiber yields an average loss of around 0.2 dB.



Fiber connectors

Demountable fiber connectors are more difficult to achieve than optical fiber splices. This is because they must maintain similar tolerance requirements to splices in order to couple light between fibers efficiently, but they must accomplish it in a removable fashion. Also, the connector design must allow for repeated connection and disconnection without problems of fiber alignment, which may lead to degradation in the performance of the transmission line at the joint. Hence to operate satisfactorily the demountable connector must provide reproducible accurate alignment of the optical fibers.

In order to maintain an optimum performance the connection must also protect the fiber ends from damage which may occur due to handling (connection and disconnection), must be insensitive to environmental factors (e.g. moisture and dust) and must cope with tensile load on the cable. Additionally, the connector should ideally be a low-cost component which can be fitted with relative ease. Hence optical fiber connectors may be considered in three major areas, which are:

- the fiber termination, which protects and locates the fiber ends;
- the fiber end alignment to provide optimum optical coupling;
- the outer shell, which maintains the connection and the fiber alignment, protects the fiber ends from the environment and provides adequate strength at the joint.

Cylindrical ferrule connectors

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

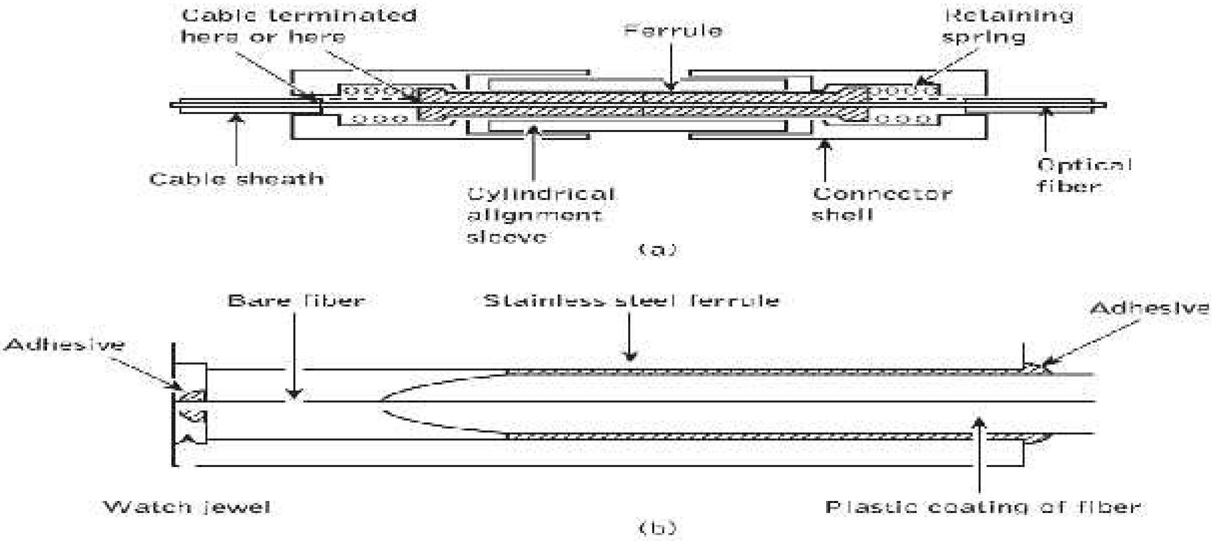


Figure Ferrule connectors: (a) structure of a basic ferrule connector; (b) structure of a watch jewel connector ferrule

It is essential with this type of connector that the fiber end faces are smooth and square (i.e. perpendicular to the fiber axis). This may be achieved with varying success by:

- cleaving the fiber before insertion into the ferrule;
- inserting and bonding before cleaving the fiber close to the ferrule end face;
- using either (a) or (b) and polishing the fiber end face until it is flush with the end of the ferrule.

Polishing the fiber end face after insertion and bonding provides the best results but it tends to be time consuming and inconvenient, especially in the field. The fiber alignment accuracy of the basic ferrule connector is largely dependent upon the ferrule hole into which the fiber is inserted. Hence, some ferrule connectors have incorporated a watch jewel in the ferrule end face (jeweled ferrule connector), as illustrated in Figure. In this case the fiber is centered with respect to the ferrule through the watch jewel hole. The use of the watch jewel allows the close diameter and tolerance requirements of the ferrule end face hole to be obtained more easily than simply through drilling of the metallic ferrule end face alone. Nevertheless, typical concentricity errors between the fiber core and the outside diameter of the jeweled ferrule are in the range 2 to 6 μm giving insertion

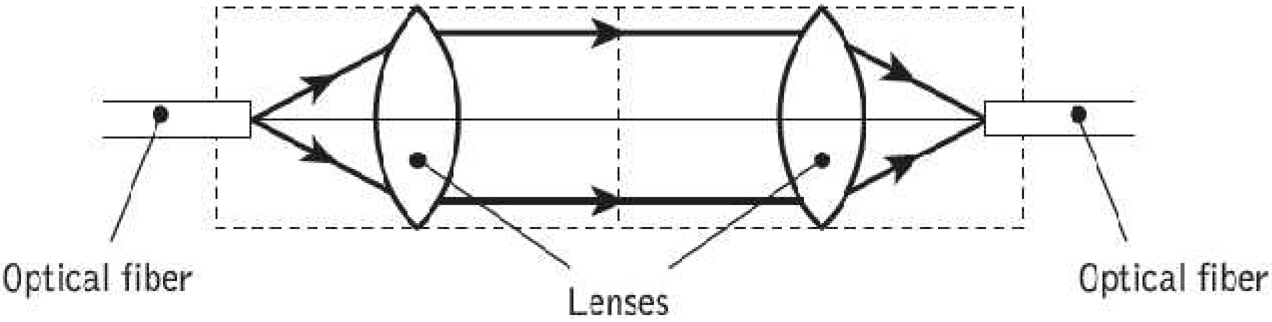


Figure Schematic illustration of an expanded beam connector showing the principle of operation

Also, the longitudinal separation between the two mated halves of the connector ceases to be critical. However, this is achieved at the expense of more stringent angular alignment. Nevertheless, expanded beam connectors are useful for multifiber connection and edge connection for printed circuit boards where lateral and longitudinal alignment are frequently difficult to achieve.

Two examples of lens-coupled expanded beam connectors are illustrated in Figure The connector shown in Figure utilized spherical microlenses for beam expansion and reduction. It exhibited average losses of 1 dB which were reduced to 0.7 dB with the application of an antireflection coating on the lenses and the use of graded index fiber of 50 µm core diameter. A similar configuration has been used for single-mode fiber connection in which the lenses have a 2.5 mm diameter. Again with antireflection-coated lenses, average losses around 0.7 dB were obtained using single-mode fibers of 8 µm core diameter. Furthermore, successful single-mode fiber connection has been achieved with a much smaller (250 µm diameter) sapphire ball lens expanded beam design.

In this case losses in the range 0.4 to 0.7 dB were demonstrated over 1000 connections. Figure shows an expanded beam connector which employs a molded spherical lens. The fiber is positioned approximately at the focal length of the lens in order to obtain a collimated beam and hence minimize lens-to-lens longitudinal misalignment effects. A lens alignment sleeve is used to minimize the effects of angular misalignment which, together with a ferrule, grommet, spring and external housing, provides the complete connector structure. The repeatability of this relatively straightforward lens design was found to be good, incurring losses of around 0.7 dB.

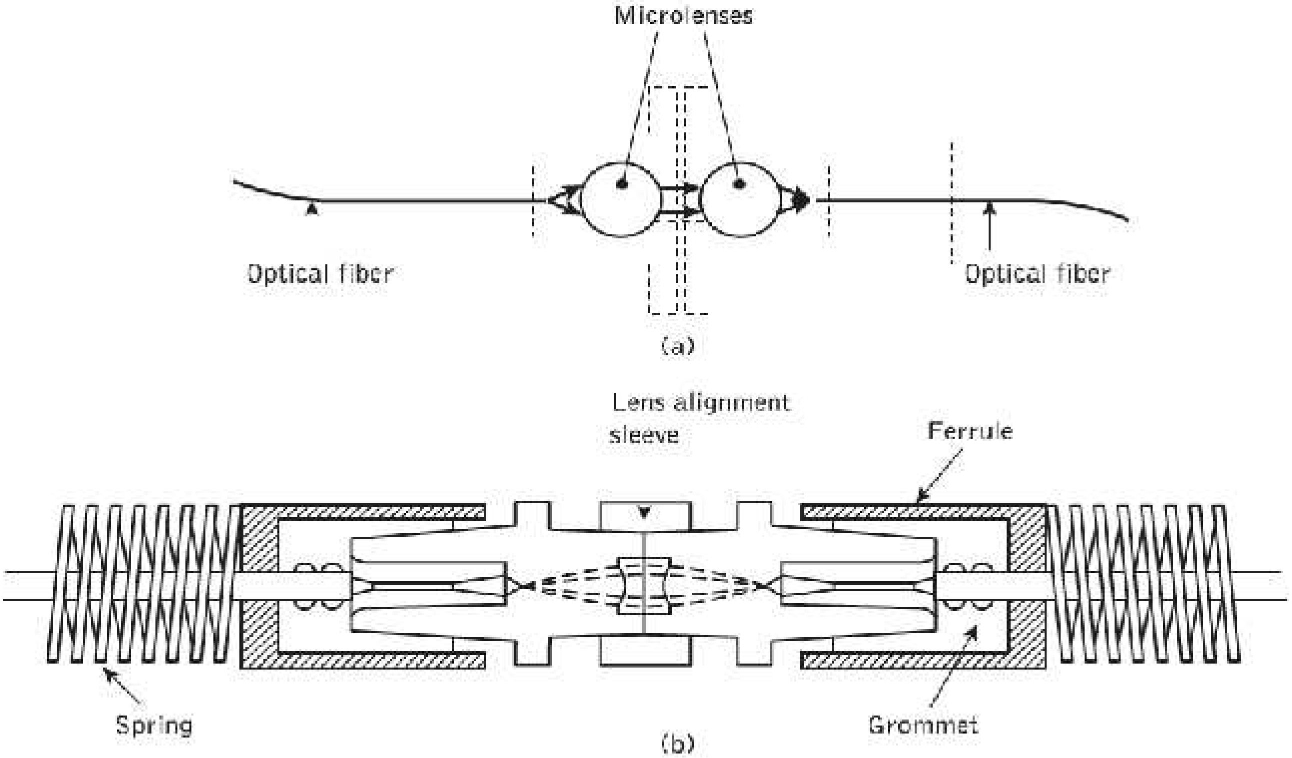


Figure Lens-coupled expanded beam connectors: (a) schematic diagram of a connector with two microlenses making a 1:1 image of the emitting fiber upon the receiving one; (b) molded plastic lens connector assembly

Fiber couplers

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

Optical fiber couplers are often passive devices in which the power transfer takes place either: (a) through the fiber core cross-section by butt jointing the fibers or by using some form of imaging optics between the fibers (core interaction type); or (b) through the fiber surface and normal to its axis by converting the guided core modes to both cladding and refracted modes which then enable the power-sharing mechanism (surface interaction type).

Multiport optical fiber couplers can also be subdivided into the following three main groups, as illustrated in Figure

1. Three- and four-port* couplers, which are used for signal splitting, distribution and combining.

2. Star couplers, which are generally used for distributing a single input signal to multiple outputs.

3. Wavelength division multiplexing (WDM) devices, which are a specialized form of coupler designed to permit a number of different peak wavelength optical signals to be transmitted in parallel on a single fiber.

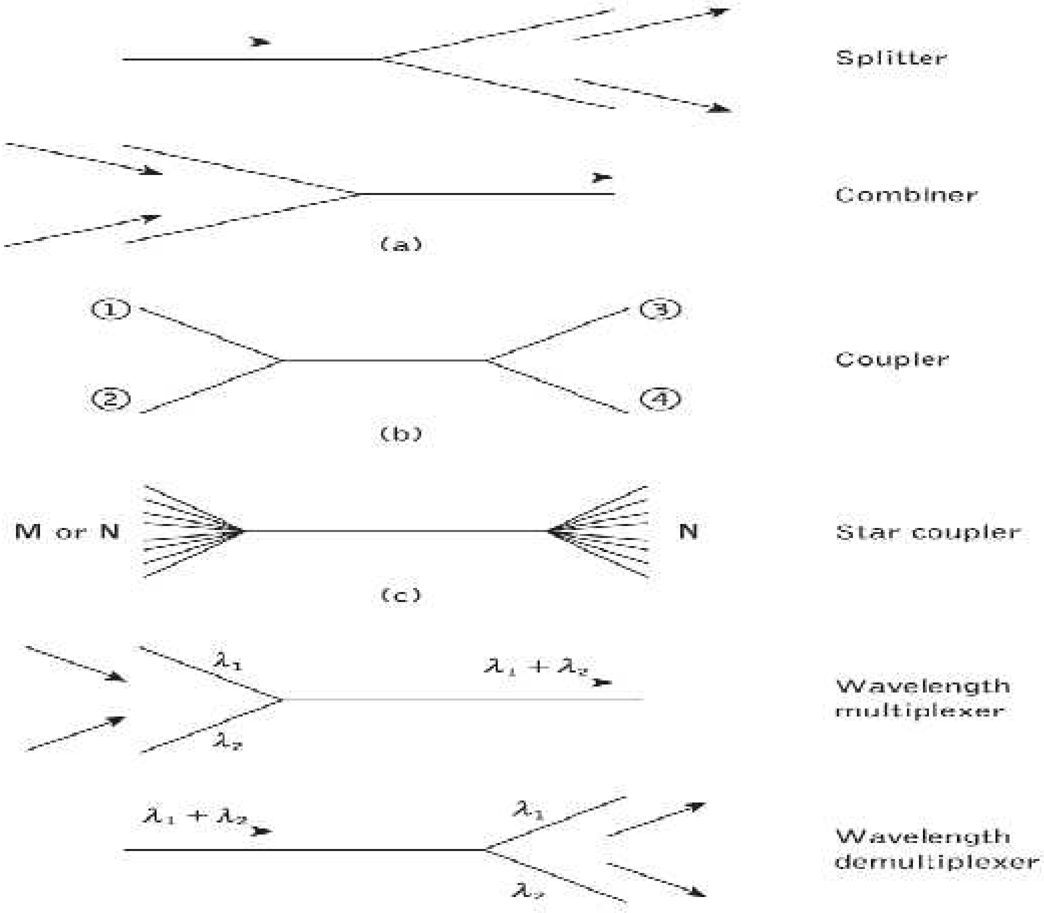
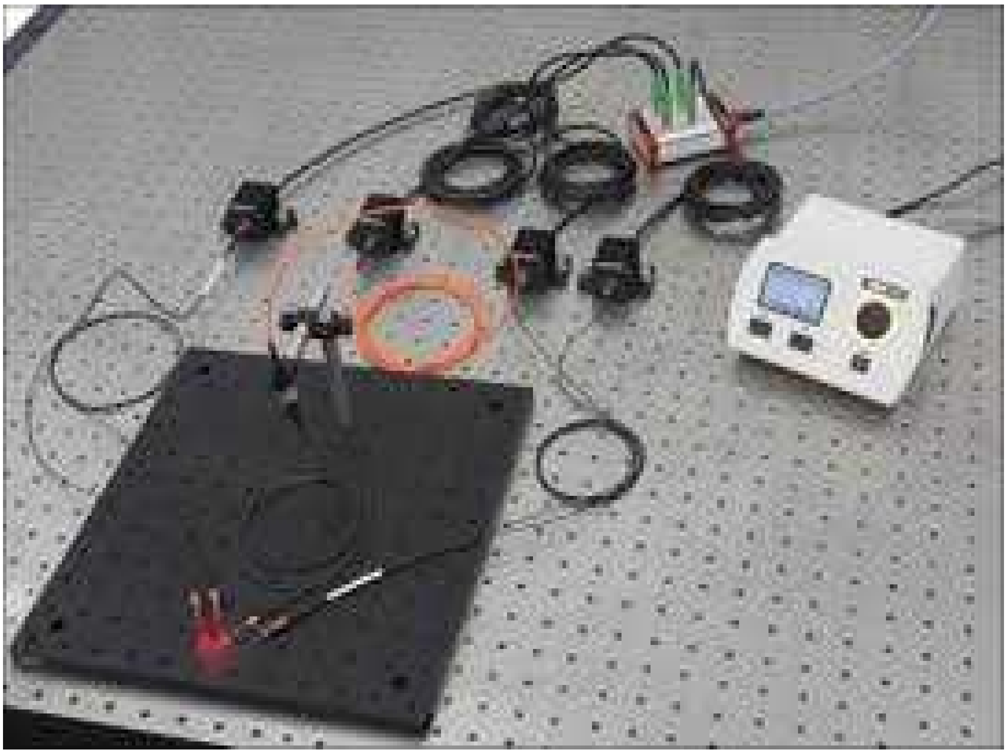


Figure Optical fiber coupler types and functions: (a) three-port couplers; (b) four-port coupler; (c) star coupler; (d) wavelength division multiplexing and demultiplexing couplers

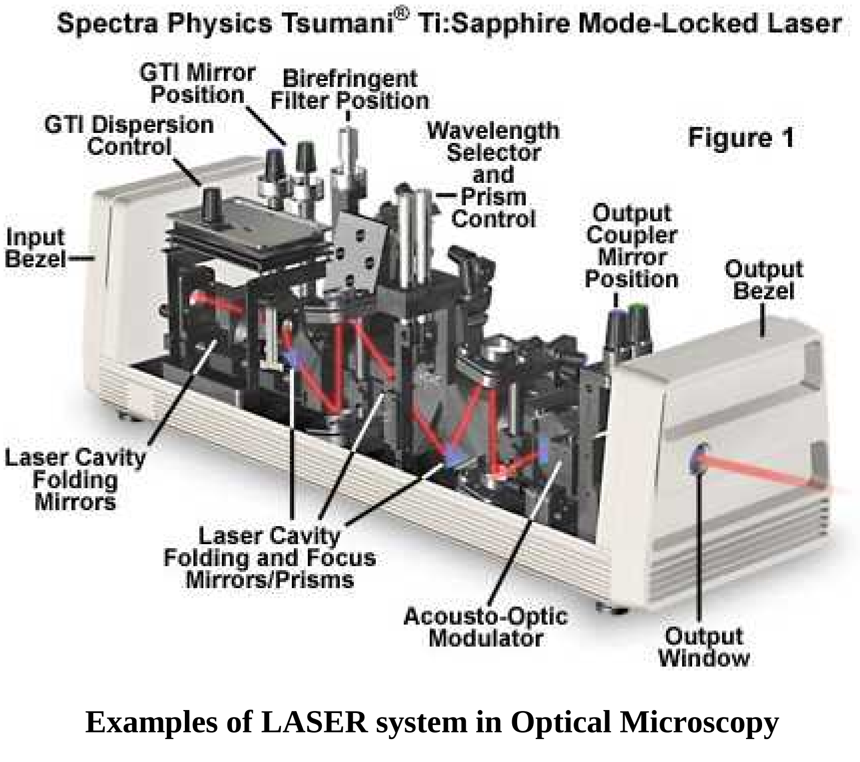
In this context WDM couplers either combine the different wavelength optical signal onto the fiber (i.e. multiplex) or separate the different wavelength optical signals output from the fiber (i.e. demultiplex). Ideal fiber couplers should distribute light among the branch fibers with no scattering loss† or the generation of noise, and they should function with complete insensitivity to factors including the distribution of light between the fiber modes, as well as the state of polarization of the light. Unfortunately, in practice passive fiber couplers do not display all of the above properties and hence the characteristics of the devices affect the performance of optical fiber networks.

This technique, which can provide a bidirectional coupling capability, is well suited for use with multimode step index fibers but may incur higher excess losses than other methods as all the input light cannot be coupled into the output fibers. Another coupling technique is to incorporate a beam splitter element between the fibers. The semitransparent mirror method provides an ingenious way to accomplish such a fiber coupler, as shown in Figure. A partially reflecting surface can be applied directly to the fiber end face cut at an angle of 45° to form a thin-film beam splitter.

APPLICATIONS



Examples of Fiber coupled LEDs for Optogenetics



Examples of LASER system in Optical Microscopy

POST TEST-MCQ TYPE

1. The radiation emission process (emission of a proton at frequency) can occur in how many ways.
a) Two
b) Three
c) Four
d) One

2. The lower energy level contains more atoms than upper level under the conditions of
a) Isothermal packaging
b) Population inversion
c) Thermal equilibrium
d) Pumping

3. Which of the following in the laser occurs when photon colliding with an excited atom causes the stimulated emission of a second photon.
a) Light amplification
b) Attenuation
c) Dispersion
d) Population inversion

4. Which of the following factors does not cause divergence of the collimated beam from a GRIN-rod lens?
a) Lens cut length
b) Size of fiber core
c) Refractive index profile
d) Chromatic aberration
5. Which is used when the optical emission results from the application of electric field.
a) Radiation
b) Efficiency
c) Electro-luminescence
d) Magnetron oscillator

6. Population inversion is obtained at a p-n junction by
a) Heavy doping of p-type material
b) Heavy doping of n-type material
c) Light doping of p-type material
d) Heavy doping of both p-type and n-type material

7. The absence of ________________ in LEDs limits the internal quantum efficiency.
a) Proper semiconductor
b) Adequate power supply
c) Optical amplification through stimulated emission
d) Optical amplification through spontaneous emission

8. What is the use of interposed optics in expanded beam connectors?

a) To achieve lateral alignment less critical than a butt-joined fiber connector

b) To make a fiber loss free

c) To make a fiber dispersive

d) For index-matching

9. Determine the internal quantum efficiency generated within a device when it has a radiative recombination lifetime of 80 ns and total carrier recombination lifetime of 40 ns.

a) 20 %

b) 80 %

c) 30 %

d) 40 %

10. The Lambertian intensity distribution __________ the external power efficiency by some percent.

a) Reduces

b) Does not affects

c) Increases

d) Have a negligible effect

11. Determine coupling efficiency into the fiber when GaAs LED is in close proximity to fiber core having numerical aperture of 0.3.

a) 0.9

b) 0.3

c) 0.6

d) 0.12

12. The amount of radiance in planer type of LED structures is

a) Low

b) High

c) Zero

d) Negligible

13. In surface emitter LEDs, more advantage can be obtained by using

a) BH structures

b) QC structures

c) DH structures

d) Gain-guided structure

14. In a multimode fiber, much of light coupled in the fiber from an LED is

a) Increased

b) Reduced

c) Lost

d) Unaffected

15. The InGaAsP is emitting LEDs are realized in terms of restricted are

a) Length strip geometry

b) Radiance

c) Current spreading

d) Coupled optical power

16. The internal quantum efficiency of LEDs decreasing ________________ with _________________ temperature.

a) Exponentially, decreasing

b) Exponentially, increasing

c) Linearly, increasing

d) Linearly, decreasing

17. The optical 3 dB point occurs when currents ratio is equal to

a) 8/3

b) 2/2

c) 1/2

d) 3/4

18. Laser modes are generally separated by few

a) Tenths of micrometer

b) Tenths of nanometer

c) Tenths of Pico-meter

d) Tenths of millimeter

19. The spectral width of emission from the single mode device is

a) Smaller than broadened transition line-width

b) Larger than broadened transition line-width

c) Equal the broadened transition line-width

d) Cannot be determined

20. Gain guided laser structure are

a) Chemical laser

b) Gas laser

c) DH injection laser

d) Quantum well laser

21. In a DH laser, the sides of cavity are formed by

a) Cutting the edges of device

b) Roughening the edges of device

c) Softening the edges of device

d) Covering the sides with ceramics

22. In Buried hetero-junction (BH) lasers, the optical field is confined within
a) Transverse direction
b) Lateral direction
c) Outside the strip
d) Both transverse and lateral direction

23. Quantum well lasers are also known as
a) BH lasers
b) DH lasers
c) Chemical lasers
d) Gain-guided lasers

24. Better confinement of optical mode is obtained in
a) Multi Quantum well lasers
b) Single Quantum well lasers
c) Gain guided lasers
d) BH lasers

25. The phenomenon resulting in the electrons to jump from one state to another each time emitting of photon is known as
a) Inter-valence band absorption
b) Mode hopping
c) Quantum cascading
d) Quantum confinement

26. Which lasers are presently the major laser source for optical fiber communications?
a) Semiconductor
b) Non-Semiconductor
c) Injection
d) Solid-state

27. It is a resonant cavity formed by two parallel reflecting mirrors separated by a mirror separated by a medium such as air or gas is?
a) Optical cavity
b) Wheatstone’s bridge
c) Oscillator
d) Fabry-perot resonator

28. Which of the following co-dopant is NOT employed by neodymium and erbium doped silica fiber lasers?
a) Phosphorus pent oxide
b) Germania
c) Nitrogen
d) Alumina

29. Dopants levels in glass fiber lasers are generally

a) Low

b) High

c) Same as that of GRIN rod lens laser

d) Same as that of semiconductor laser

30. The lasing output of the basic Fabry-perot cavity fiber is restricted to between

a) 1 and 2 nm

b) 5 and 10 nm

c) 3 and 6 nm

d) 15 and 30 nm

31. In Fabry-perot laser, the lower threshold is obtained by

a) Increasing the refractive index

b) Decreasing the refractive index

c) Reducing the slope efficiency

d) Increasing the slope efficiency

32. $Y_3A_{l5}\ O_{12}$ is a molecular formula for

a) Ytterbium aluminate

b) Yttrium oxide

c) Ytterbium oxy-aluminate

d) Yttrium-aluminum garnet

33**.** A measure of amount of optical fiber emitted from source that can be coupled into a fiber is termed as

a) Radiance

b) Angular power distribution

c) Coupling efficiency

d) Power-launching

34. How many types of misalignments occur when joining compatible fiber?

a) One

b) Two

c) Five

d) Three

35. Losses caused by factors such as core-cladding diameter, numerical aperture, relative refractive index differences, different refractive index profiles, fiber faults are known as

a) Intrinsic joint losses

b) Extrinsic losses

c) Insertion losses

d) Coupling losses

36. A permanent joint formed between two different optical fibers in the field is known as a
a) Fiber splice
b) Fiber connector
c) Fiber attenuator
d) Fiber dispersion

37. How many types of fiber splices are available?
a) One
b) Two
c) Three
d) Four

38. What is the main requirement with the fibers that are intended for splicing?
a) Smooth and oval end faces
b) Smooth and square end faces
c) Rough edge faces
d) Large core diameter

39. In score and break process, which of the following is NOT used as a cutting tool?
a) Diamond
b) Sapphire
c) Tungsten carbide
d) Copper

40. The heating of the two prepared fiber ends to their fusing point with the application of required axial pressure between the two optical fibers is called as
a) Mechanical splicing
b) Fusion splicing
c) Melting
d) Diffusion

41. Which of the following is not used as a flame heating source in fusion splicing?
a) Microprocessor torches
b) Ox hydric burners
c) Electric arc
d) Gas burner

42. Which is caused by surface tension effects between the two fiber ends during fusing.
a) Pre-fusion
b) Diffusion
c) Self-alignment
d) Splicing

43. What are formed by sandwiching the butted fiber ends between a V-groove glass substrate and a flat glass retainer plate.
a) Springroove splices
b) V-groove splices
c) Elastic splices
d) Fusion splices

44. What is the use of an index-matching material in the connector between the two jointed fibers?
a) To decrease the light transmission through the connection
b) To increase the light transmission through the connection
c) To induce losses in the fiber
d) To make a fiber dispersive

45. How many categories of fiber connectors exist?
a) One
b) Three
c) Two
d) Four

46. What is the use of watch jewel in cylindrical ferrule connector?
a) To obtain the diameter and tolerance requirements of the ferrule
b) For polishing purposes
c) Cleaving the fiber
d) To disperse a fiber

47. In connectors, the fiber ends are separated by some gap. This gap ranges from
a) 0.040 to 0.045 mm
b) 0.025 to 0.10 mm
c) 0.12 to 0.16 mm
d) 0.030 to 0.2mm

CONCLUSION

In this unit, the various optical sources, materials and fiber splicing were learnt. The principles of different optical sources and power launching-coupling methods were described in detailed.

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ASSIGNMENT

1. Draw and explain the LED structures based Double Heterostucture configuration
2. Discuss the principle of operation of LASER diodes.
3. What are the effects of temperature on the performance of a LASER diode?
4. Explain the lensing schemes used to improve optical source - to- fiber coupling efficiency.
5. What are the advantages of Quantum well LASERS?
6. Explain briefly the three key processes involved in the laser action.
7. Describe for a fabry-perot resonator laser diode, modes and threshold conditions. Obtain its rate equations for steady state output.
8. Describe various fiber splicing techniques with their diagrams.
9. Describe the various types of fiber connectors and couplers.
10. Explain mechanical splices with neat diagrams.

AIM & OBJECTIVES

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

PRE TEST-MCQ TYPE

1. How many design considerations are considered while determining the receiver performance?
a) Three
b) Two
c) One
d) Four

2. Which circuits extends the dynamic range of the receiver?
a) Monolithic
b) Trans-impedance
c) Automatic Error Control (AEC)
d) Automatic Gain Control (AGC)

3. The sensitivity of the low-impedance configuration is ____________
a) Good
b) Poor
c) Great
d) Same as that of high-impedance configuration

4. What is generally used to determine the receiver performance characteristics?
a) Noise
b) Resistor
c) Dynamic range & sensitivity characteristics
d) Impedance

UNIT IV FIBER OPTIC RECEIVER AND MEASUREMENTS

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

THEORY
Introduction

Fundamental Receiver Operation

The receiver must first detect weak, distorted signal and then make decisions 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

  - Digital Signal Transmission
  - Error Sources
- Digital Receiver Performance
  - Probability of Error
  - Receiver Sensitivity
  - The Quantum Limit
- Coherent Detection
- Analog Receiver

Optical Receiver Operation

Digital Signal Transmission

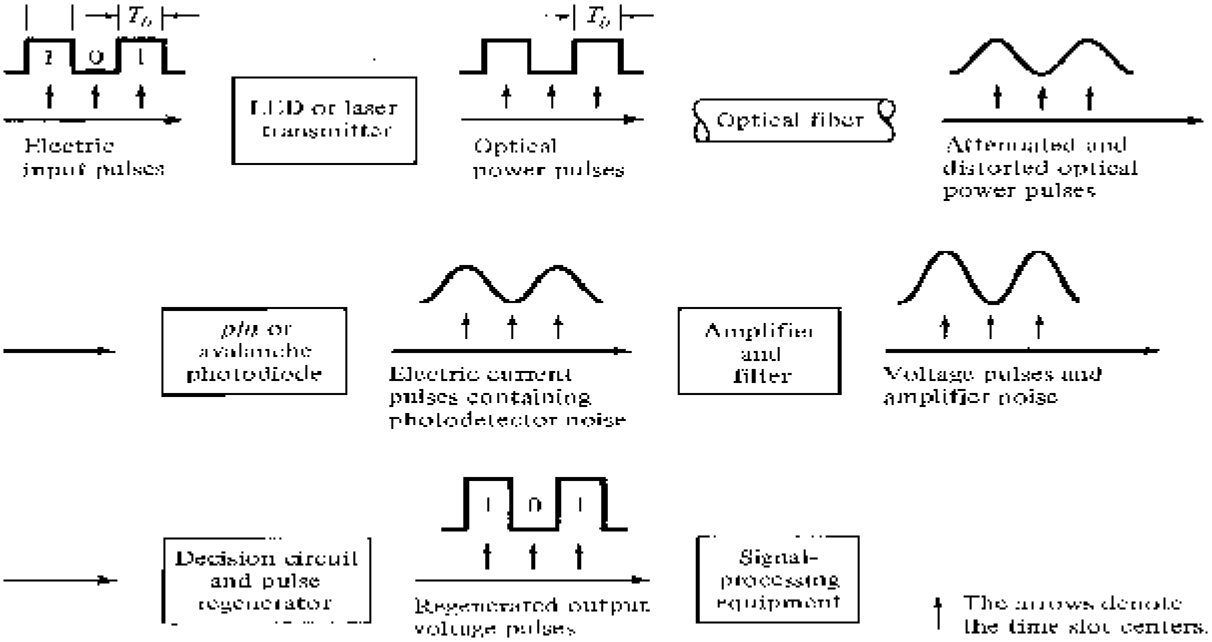


Figure Signal path through an optical data link.

- A typical digital fiber transmission link is shown in Figure. The transmitted signal is a two- level binary data stream consisting of either a ‘0’ or a ‘1’ in a bit period T_b.
- The simplest technique for sending binary data is amplitude-shift keying, wherein a voltage level is switched between on or off values.
- The resultant signal wave thus consists of a voltage pulse of amplitude V when a binary 1 occurs and a zero-voltage-level space when a binary 0 occurs.
- An electric current i(t) can be used to modulate directly an optical source to produce an optical output power P(t).
- In the optical signal emerging from the transmitter, a ‘1’ is represented by a light pulse of duration Tb, 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 APD converts the optical signal back to an electrical format.
- A decision circuit compares the amplified signal in each time slot with a threshold level.
- If the received signal level is greater than the threshold level, a ‘1’ is said to have been received.
- If the voltage is below the threshold level, a ‘0’ is assumed to have been received.

Error Sources

- Errors in the detection mechanism can arise from various noises and disturbances associates with the signal detection system.
- The two most common samples of the spontaneous fluctuations are shot noise and thermal noise.
- Shot noise arises in electronic devices because of the discrete nature of current flow in the device
- Thermal noise arises from the random motion of electrons in a conductor.
- The random arrival rate of signal photons produces a quantum (or shot) noise at the photodetector.
- This noise depends on the signal level.
- This noise is of particular importance for PIN receivers that have large optical input levels and for APD receivers.
- When using an APD, an additional shot noise arises from the statistical nature

of the multiplication process. This noise level increases with increasing avalanche gain *M*.

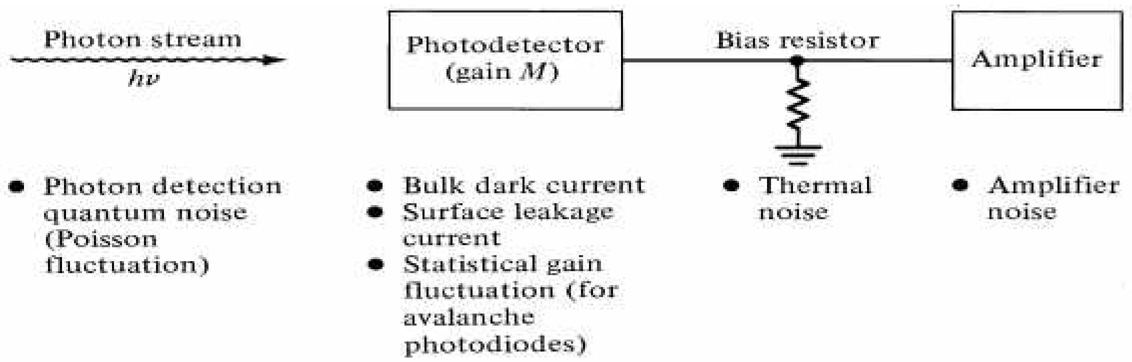


Figure Noise sources and disturbances in the optical pulse detection mechanism.

- Thermal noises arising from the detector load resistor and from the amplifier electronics tend to dominate in applications with low SNR when a PIN photodiode is used.
- When an APD is used in low-optical-signal level applications, the optimum avalanche gain is determined by a design tradeoff between the thermal noise and the gain-dependent quantum noise.
- The primary photocurrent generated by the photodiode is a time-varying Poisson process.
- If the detector is illuminated by an optical signal *P*(*t*), then the average number of electron-hole pairs generated in a time t is

$$\overline{N} = \frac{\eta}{h\nu}\int_0^{\tau} P(t)\,dt = \frac{\eta E}{h\nu}$$

Where h is the detector quantum efficiency, *h*n is the photon energy, and *E* is the energy received in a time interval.

- The actual number of electron-hole pairs *n* that are generated fluctuates from the average according to the Poisson distribution

where *P*r(*n*) is the probability that *n* electrons are emitted in an interval t. For a detector with a mean avalanche gain *M* and an ionization rate ratio *k*, the excess noise factor *F*(*M*) for electron injection is

$$F(M) = kM + \left(2 - \frac{1}{M}\right)(1 - k)$$

Or

$$F(M) \simeq M^{x}$$

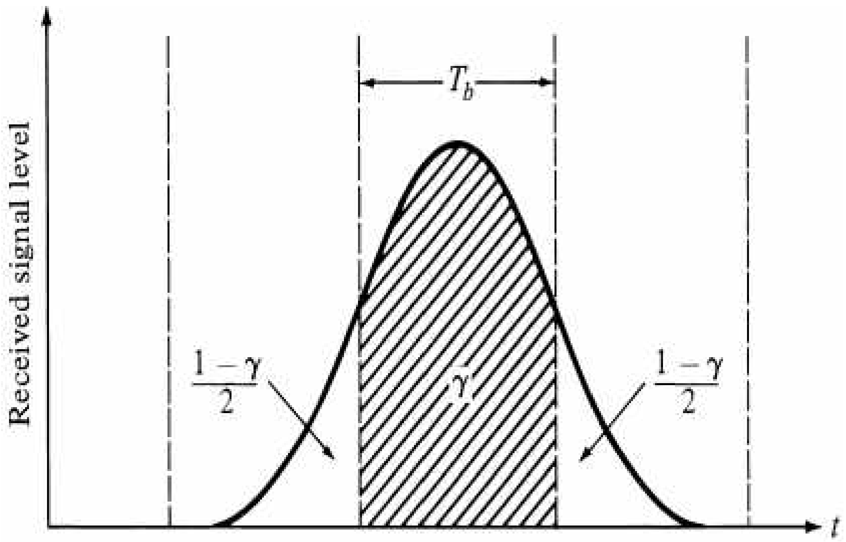


Figure Pulse spreading in an optical signal that leads to ISI.

Where the factor x ranges between 0 and 1.0 depending on the photodiode material. A further error source is attributed to inter symbol interference (ISI), which results from pulse spreading in the optical fiber. The fraction of energy remaining in the appropriate time slot is designated by g, so that 1-g is the fraction of energy that has spread into adjacent time slots.

Receiver Configuration

A typical optical receiver is shown in Figure. The three basic stages of the receiver are a photodetector, an amplifier, and an equalizer. The photo-detector can be either an APD with a mean gain *M* or a PIN for which M=1. The photodiode has a quantum efficiency h and a capacitance C_d. The detector bias resistor has a resistance R_b which generates a thermal noise current *i*b(*t*).

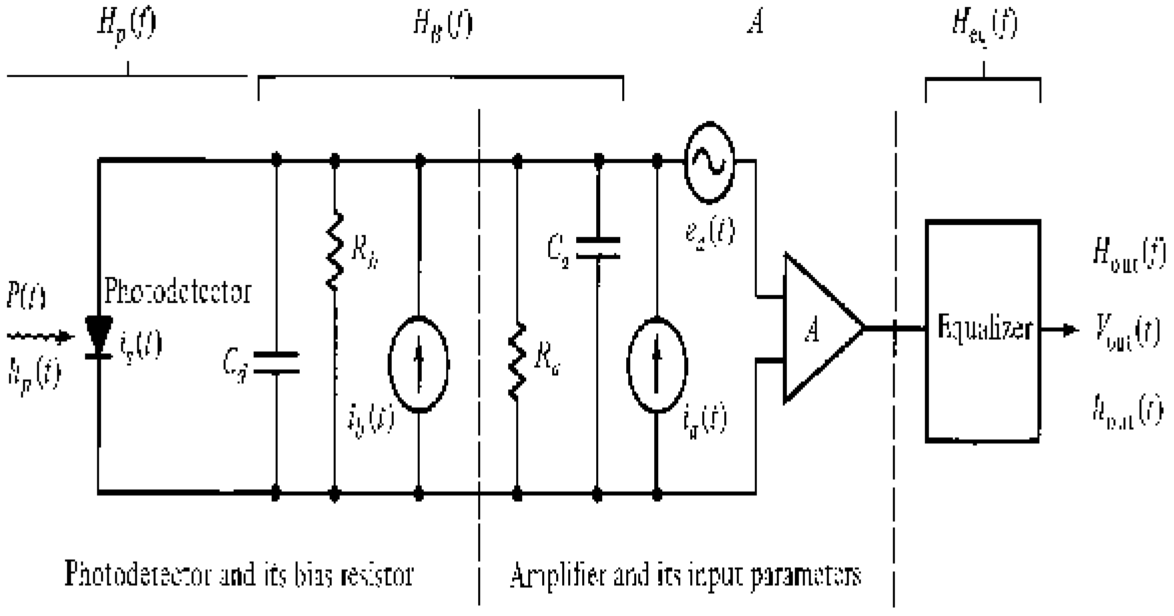


Figure Schematic diagram of a typical optical receiver.

Amplifier Noise Sources:

The input noise current source ia(t) arises from the thermal noise of the amplifier input resistance Ra; The noise voltage source ea(t) represents the thermal noise of the amplifier channel. The noise sources are assumed to be Gaussian in statistics, flat in spectrum (which characterizes white noise), and uncorrelated (statistically independent).

The Linear Equalizer:

The equalizer is normally a linear frequency shaping filter that is used to mitigate the effects of signal distortion and inter symbol interference (ISI). The equalizer accepts the combined frequency response of the transmitter, the fiber, and the receiver, and transforms it into a signal response suitable for the following signal processing electronics.

The binary digital pulse train incident on the photo-detector can be described by

$$P(t)=\sum_{n=-\infty}^{\infty} b_n h_p(t-nT_b)$$

Here, P(t) is the received optical power, Tb is the bit period, b_n is an amplitude parameter representing the nth message digit, and hp(t) is the received pulse shape.

Let the nonnegative photodiode input pulse $h_p(t)$ be normalized to have unit area

$$\int_{-\infty}^{\infty} h_p(t)\,dt=1$$

Then b_n represents the energy in the n^{th} pulse.

The mean output current from the photodiode at time *t* resulting from the pulse train given previously is

$$\langle i(t)\rangle=\frac{\eta q}{h\nu}MP(t)=R_0\sum_{n=-\infty}^{\infty} b_n h_p(t-nT_b)$$

Where *R*o = h*q*/*h*n is the photodiode responsivity. The above current is then amplified and filtered to produce a mean voltage at the output of the equalizer.

Probability of error:

The digital receiver performance can be evaluated by measuring the probability of error and quantum limit. In practice, several standards ways are available to measuring the rate of error occurrences in a digital data stream.

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

The Quantum Limit:

Consider an ideal photodetector which has unity quantum efficiency and which produces no dark current that is no electron hole pairs are generated in the absence of an optical pulse.

With this condition it is possible to find the minimum received optical power required for a specific bit error rate performance in a digital system. This minimum received power level is known as the quantum limit, since all system parameters are assumed ideal and the performance is only limited by the photodetection statistics.

Assume that an optical pulse of energy E falls on the photodetector in a time interval τ. This can only be interpreted by the receiver as a 0 pulse if no electron hole pairs are generated with the pulse present. The probability that n=0 electrons are emitted in a time interval τ is

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

Thus for a given error probability $P_r(0)$, we can find the minimum energy E required at a specific wavelength λ.

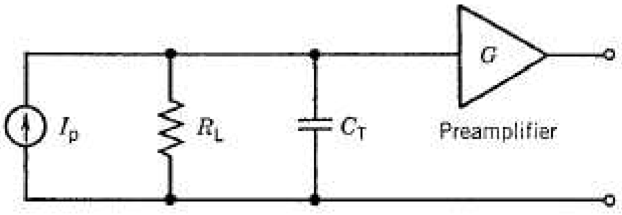
Preamplifier:

Front End

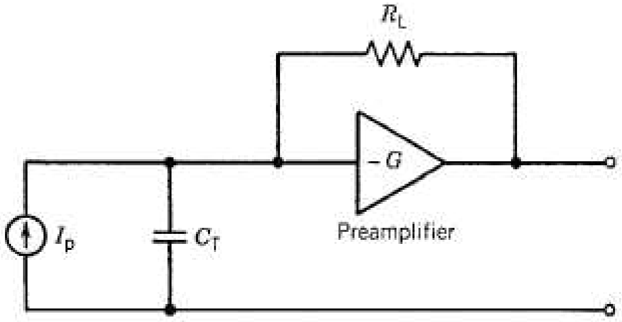
The front end of a receiver consists of a photodiode followed by a preamplifier. The optical signal is coupled onto the photodiode by using a coupling scheme similar to that used for optical transmitters but coupling is often used in practice. The photodiode converts the optical bit stream into an electrical time-varying signal. The role of the preamplifier is to amplify the electrical signal for further processing. The design of the front end requires a trade-off between speed and sensitivity. Since the input voltage to the preamplifier can be increased by using a large load resistor *R L*, a high-impedance front end is often used. Furthermore, as discussed, a large *RL* reduces the thermal noise and improves the receiver sensitivity.

The main drawback of high-impedance front end is its low bandwidth given by $\Delta f = (2\pi R_L C_T)-1$, where *Rs _RL* is assumed and $C_T = C_p + C_A$ is the total capacitance, which includes the contributions from the photodiode (C_p) and the transistor used for amplification (C_A). The receiver bandwidth is limited by its slowest component. A high-impedance front end cannot be used if Δf is considerably less than the bit rate. An equalizer is sometimes used to increase the bandwidth. The equalizer acts as a filter that attenuates low-frequency components of the signal more than the high-frequency components, thereby effectively increasing the front-end bandwidth. If the receiver sensitivity is not of concern, one can simply decrease *RL* to increase the bandwidth, resulting in a low-impedance front end. Transimpedance front ends provide a configuration that has high sensitivity together with a large bandwidth. Its dynamic range is also improved compared with high-impedance front ends. As seen in Figure the load resistor is connected as a feedback resistor around an inverting amplifier.

Even though R_L is large, the negative feedback reduces the effective input impedance by a factor of G, where G is the amplifier gain. The bandwidth is thus enhanced by a factor of G compared with high impedance front ends. Transimpedance front ends are often used in optical receivers because of their improved characteristics. A major design issue is related to the stability of the feedback loop.



(a)



(b)

The receiver amplifiers are the front end preamplifiers. Preamplifier bandwidth must be greater than or equal to signal bandwidth. It must reduce all source of noise. It must have high receiver sensitivity. There are three basic preamplifier structures

1. Low –Impedance preamplifier

2. High- impedance preamplifier

3. Trans-impedance preamplifier

The preamplifier should have low noise level, high bandwidth, high dynamic range, high sensitivity and high gain.

Fiber attenuation measurements

Fiber attenuation measurement techniques have been developed in order to determine the total fiber attenuation of the relative contributions to this total from both absorption losses and scattering losses. The overall fiber attenuation is of greatest interest to the system designer, but the relative magnitude of the different loss mechanisms is important in the development and fabrication of low-loss fibers. Measurement techniques to obtain the total fiber attenuation give either the spectral loss characteristic or the loss at a single wavelength (spot measurement).

Total fiber attenuation

A commonly used technique for determining the total fiber attenuation per unit length is the cut- back or differential method. Figure shows a schematic diagram of the typical experimental setup for measurement of the spectral loss to obtain the overall attenuation spectrum for the fiber. It consists of a ‘white’ light source, usually a tungsten halogen or xenon are lamp. The focused light is mechanically chopped at a low frequency of a few hundred hertz. This enables the lock-in amplifier at the receiver to perform phase-sensitive detection.

The chopped light is then fed through a monochromator which utilizes a prism or diffraction grating arrangement to select the required wavelength at which the attenuation is to be measured. Hence the light is filtered before being focused onto the fiber by means of a microscope objective lens. A beam splitter may be incorporated before the fiber to provide light for viewing optics and a reference signal used to compensate for output power fluctuations. When the measurement is performed on multimode fibers it is very dependent on the optical launch conditions. Therefore unless the launch optics are arranged to give the steady-state mode distribution at the fiber input, or a dummy fiber is used, then a mode scrambling device is attached to the fiber within the first meter.

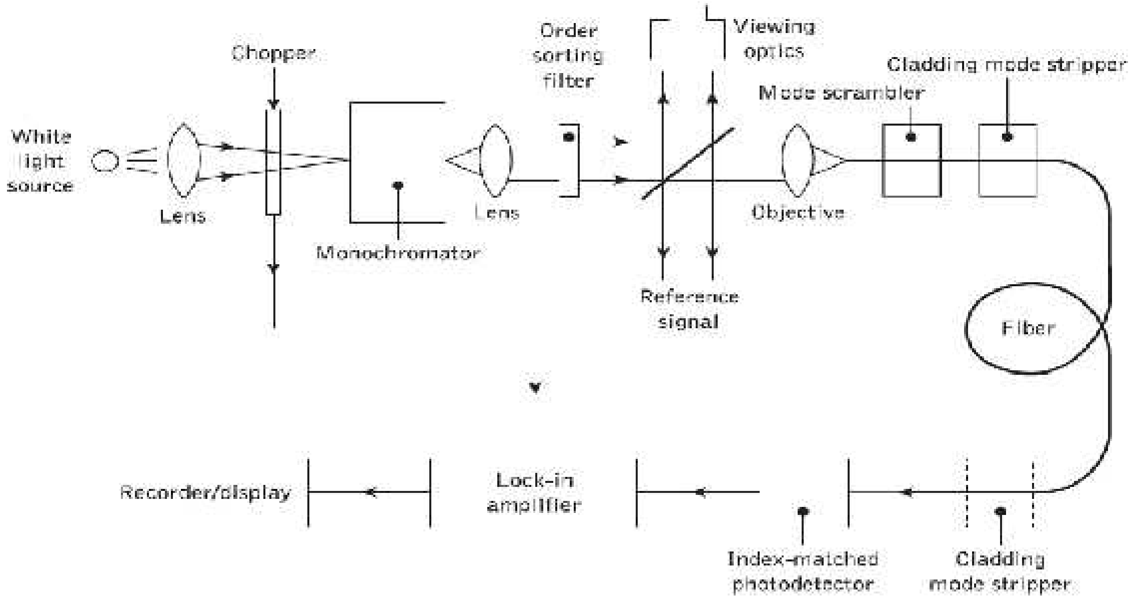


Figure A typical experimental arrangement for the measurement of spectral loss in optical fibers using the cut-back technique

The fiber is also usually put through a cladding mode stripper, which may consist of an S-shaped groove cut in the Teflon and filled with glycerine. This device removes light launched into the fiber cladding through radiation into the index-matched (or slightly higher refractive index) glycerine. A mode stripper can also be included at the fiber output end to remove any optical power which is scattered from the core into the cladding down the fiber length. This tends to be pronounced when the fiber cladding consists of a low-refractive-index silicone resin.

The optical power at the receiving end of the fiber is detected using a *p–i–n* or avalanche photodiode. In order to obtain reproducible results the photodetector surface is usually index matched to the fiber output end face using epoxy resin or an index-matching gell. Finally, the electrical output from the photodetector is fed to a lock-in amplifier, the output of which is recorded.

The cut-back method* involves taking a set of optical output power measurements over the required spectrum using a long length of fiber (usually at least a kilometer). This fiber is generally uncabled having only a primary protective coating. Increased losses due to cabling do not tend to change the shape of the attenuation spectrum as they are entirely radiative, and for multimode fibers are almost wavelength independent. The fiber is then cut back to a point 2m from the input end and, maintaining the same launch conditions, another set of power output measurements is taken.

$$\alpha_{dB} = \frac{10}{L_1 - L_2} \log_{10} \frac{P_{02}}{P_{01}}$$

L_1 and L_2 are the original and cut-back fiber lengths respectively, and P_{01} and P_{02} are the corresponding output optical powers at a specific wavelength from the original and cut-back fiber lengths. Hence when L_1 and L_2 are measured in kilometers, α_{dB} has units of dB km−1.

$$\alpha_{dB} = \frac{10}{L_1 - L_2} \log_{10} \frac{V_2}{V_1}$$

Where V_1 and V_2 correspond to output voltage readings from the original fiber length and the cut-back fiber length respectively.

Fiber absorption loss measurement

It was indicated in the preceding section that there is a requirement for the optical fiber manufacturer to be able to separate the total fiber attenuation into the contributions from the major loss mechanisms. Material absorption loss measurements allow the level of impurity content within the fiber material to be checked in the manufacturing process. The measurements are based on calorimetric methods which determine the temperature rise in the fiber or bulk material resulting from the absorbed optical energy within the structure.

The apparatus shown in Figure is used to measure the absorption loss in optical fibers, was modified from an earlier version which measured the absorption losses in bulk glasses. This temperature measurement technique, illustrated diagrammatically in Figure, has been widely adopted for absorption loss measurements. The two fiber samples shown in Figure are mounted in capillary tubes surrounded by a low-refractive-index liquid (e.g. methanol) for good electrical contact, within the same enclosure of the apparatus shown in Figure. A thermocouple is wound around the fiber containing capillary tubes using one of them as a reference junction (dummy fiber).

Light is launched from a laser source (Nd: YAG or krypton ion depending on the wavelength of interest) through the main fiber (not the dummy), and the temperature rise due to absorption is measured by the thermocouple and indicated on a nanovoltmeter. Electrical calibration may be achieved by replacing the optical fibers with thin resistance wires and by passing known electrical power through one. Independent measurements can then be made using the calorimetric technique and with electrical measurement instruments.

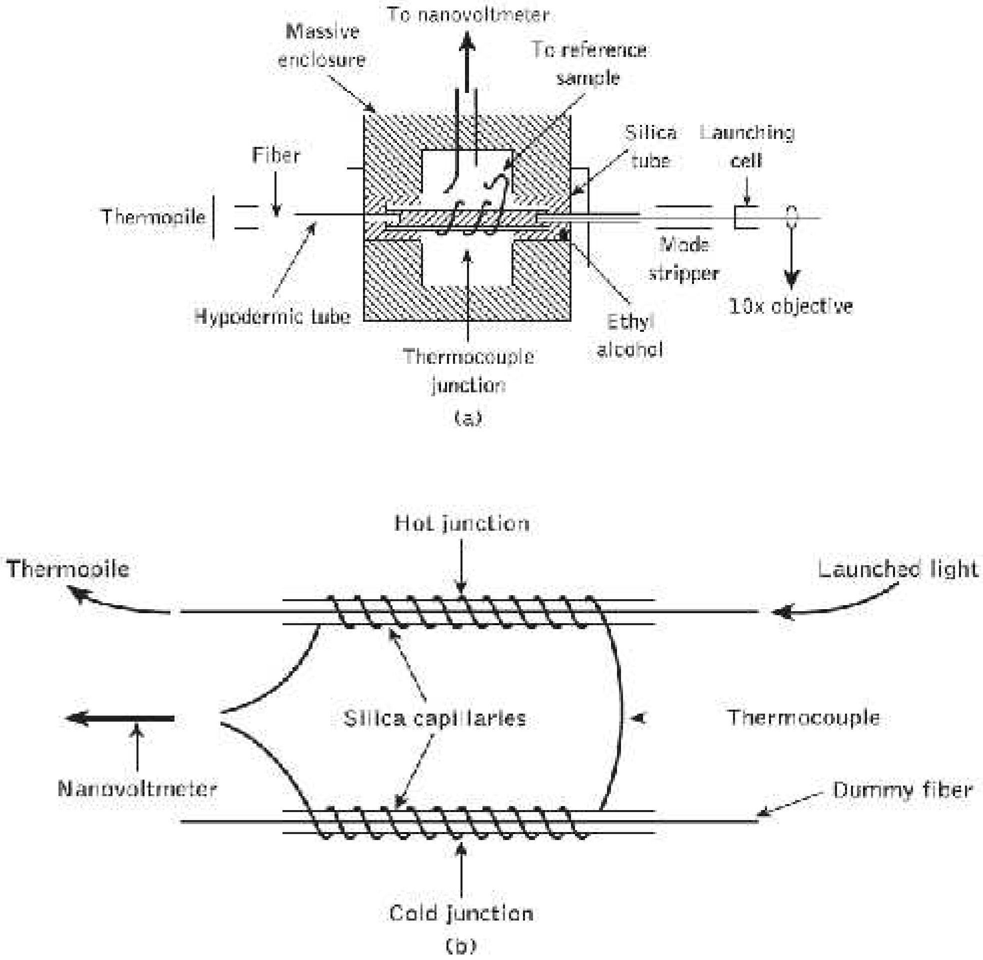


Figure Calorimetric measurement of fiber absorption losses: (a) schematic diagram of a version of the apparatus; (b) the temperature measurement technique using a thermocouple

The calorimetric measurements provide the heating and cooling curve for the fiber sample used. A typical example of this curve is illustrated in Figure. The attenuation of the fiber due to absorption α_{abs} may be determined from this heating and cooling characteristic. A time constant t_c can be obtained from a plot on a logarithmic scale against the time t, an example of which shown in Figure was obtained from the heating characteristic displayed in Figure. This corresponds to the maximum temperature rise of the fiber under test and T_t is the temperature rise at a time t. It may be observed from Figure that corresponds to a steady-state temperature for the fiber when the heat loss to the surroundings balances the heat generated in the fiber resulting from absorption at a particular optical power level.

The time constant t_c may be obtained from the slope of the straight line plotted in Figure

$$t_c = \frac{t_2 - t_1}{\ln(T_\infty - T_{t_1}) - \ln(T_\infty - T_{t_2})}$$

$$\alpha_{abs} = \frac{CT_\infty}{P_{opt} t_c} \text{ dB km}^{-1}$$

Where C is proportional to the thermal capacity per unit length of the silica capillary and the low- refractive-index liquid surrounding the fiber, and P_{opt} is the optical power propagating in the fiber under test. The thermal capacity per unit length may be calculated, or determined by the electrical calibration utilizing the thin resistance wire.

Fiber scattering loss measurement

The usual method of measuring the contribution of the losses due to scattering within the total fiber attenuation is to collect the light scattered from a short length of fiber and compare it with the total optical power propagating within the fiber. Light scattered from the fiber may be detected in a scattering cell as illustrated in the experimental arrangement shown in Figure. This may consist of a cube of six square solar cells or an integrating sphere and detector. The solar cell cube which contains index-matching fluid surrounding the fiber gives measurement of the scattered light, but careful balancing of the detectors is required in order to achieve a uniform response.

This problem is overcome in the integrating sphere which again usually contains index matching fluid but responds uniformly to different distributions of scattered light. However, the integrating sphere does exhibit high losses from internal reflections. Other variations of the scattering cell include the internally reflecting cell and the sandwiching of the fiber between two solar cells. A laser source (i.e. He–Ne, Nd: YAG, krypton ion) is utilized to provide sufficient optical power at a single wavelength together with a suitable instrument to measure the response from the detector. In order to avoid inaccuracies in the measurement resulting from scattered light which may be trapped in the fiber, cladding mode strippers are placed before and after the scattering cell.

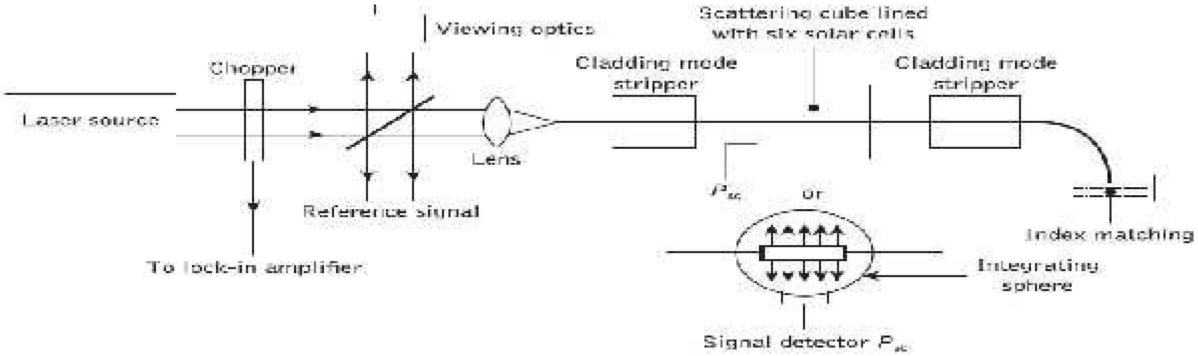


Figure An experimental setup for measurement of fiber scattering loss illustrating both the solar cell cube and integrating sphere scattering cells

These devices remove the light propagating in the cladding so that the measurements are taken only using the light guided by the fiber core. Also, to avoid reflections contributing to the optical signal within the cell, the output fiber end is index matched using either a fluid or suitable surface.

The loss due to scattering α_{SC} is given by:

$$\alpha_{sc} = \frac{10}{l(\text{km})}\log_{10}\left(\frac{P_{opt}}{P_{opt}-P_{sc}}\right)\text{dB km}^{-1}$$

where l(km) is the length of the fiber contained within the scattering cell, P_{opt} is the optical power propagating within the fiber at the cell and P_{sc} is the optical power scattered from the short length of fiber l within the cell. As $P_{opt} >> P_{sc}$, then the logarithm in equation may be expanded to give:

Since the measurements of length are generally in centimeters and the optical power is normally registered in volts, Equation can be written as:

$$\alpha_{sc} = \frac{4.343\times 10^{5}}{l(\text{cm})}\left(\frac{V_{sc}}{V_{opt}}\right)\text{dB km}^{-1}$$

Where V_{sc} and V_{opt} are the voltage readings corresponding to the scattered optical power and the total optical power within the fiber at the cell. The relative experimental accuracy (i.e. repeatability) for scatter loss measurements is in the range ±0.2 dB using the solar cell cube and around 5% with the integrating sphere. However, it must be noted that the absolute accuracy of the measurements is somewhat poorer, being dependent on the calibration of the scattering cell and the mode distribution within a multimode fiber.

Fiber dispersion measurements

Dispersion measurements give an indication of the distortion to optical signals as they propagate down optical fibers. The delay distortion which, for example, leads to the broadening of transmitted light pulses limits the information-carrying capacity of the fiber. The measurement of dispersion allows the bandwidth of the fiber to be determined. Therefore, besides attenuation, dispersion is the most important transmission characteristic of an optical fiber. As discussed, there are three major mechanisms which produce dispersion in optical fibers (material dispersion, waveguide dispersion and intermodal dispersion). The importance of these different mechanisms to the total fiber dispersion is dictated by the fiber type. For instance, in multimode fibers (especially step index), intermodal dispersion tends to be the dominant mechanism, whereas in single-mode fibers intermodal dispersion is nonexistent as only a single mode is allowed to propagate. In the single-mode case the dominant dispersion mechanism is chromatic. The dominance of intermodal dispersion in multimode fibers makes it essential that dispersion measurements on these fibers are performed only when the equilibrium mode distribution has been established within the fiber, otherwise inconsistent results will be obtained. Therefore devices such as mode scramblers or filters must be utilized in order to simulate the steady state mode distribution.

Dispersion effects may be characterized by taking measurements of the impulse response of the fiber in the time domain, or by measuring the baseband frequency response in the frequency domain. If it is assumed that the fiber response is linear with regard to power, a mathematical description in the time domain for the optical output power $P_o(t)$ from the fiber may be obtained by convoluting the power impulse response h(t) with the optical input power Pi(t) as:

$$P_o(t) = h(t) * P_i(t)$$

where the asterisk * denotes convolution. The convolution of h(t) with Pi(t) shown in Equation may be evaluated using the convolution integral where:

$$P_o(t) = \int_{-\infty}^{\infty} P_i(t-x)\,h(x)\,\mathrm{d}x$$

In the frequency domain the power transfer function *H*(w) is the Fourier transform of *h*(*t*) and therefore by taking the Fourier transforms of all the functions in Equation

$$\mathcal{P}_o(\omega) = H(\omega)\mathcal{P}_i(\omega)$$

Time domain measurement

The most common method for time domain measurement of pulse dispersion in multimode optical fibers is illustrated in Figure. Short optical pulses (100 to 400 ps) are launched into the fiber from a suitable source (e.g. A1GaAs injection laser) using fast driving electronics. The pulses travel down the length of fiber under test (around 1 km) and are broadened due to the various dispersion mechanisms. However, it is possible to take measurements of an isolated dispersion mechanism by, for example, using a laser with a narrow spectral width when testing a multimode fiber. In this case the chromatic dispersion is negligible and the measurement thus reflects only intermodal dispersion.

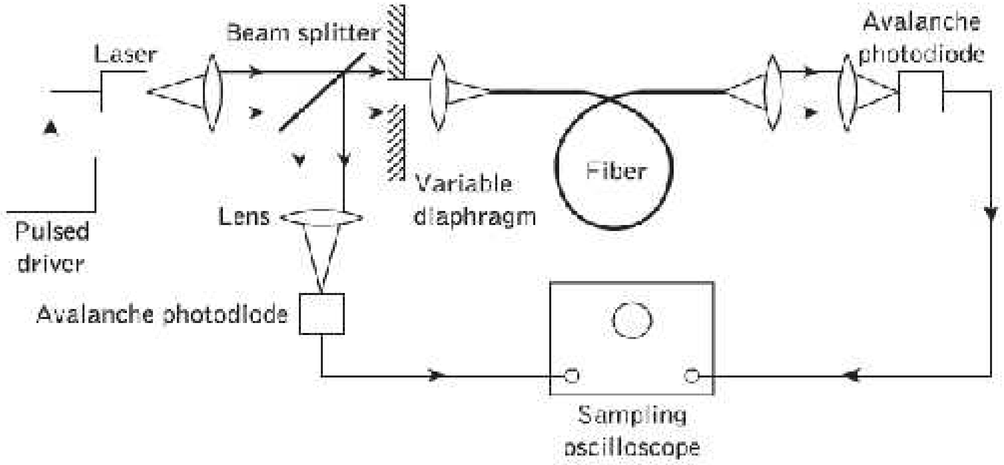


Figure Experimental arrangement for making multimode fiber dispersion measurements in the time domain.

The pulses are received by a high-speed photodetector (i.e. avalanche photodiode) and are displayed on a fast sampling oscilloscope. A beam splitter is utilized for triggering the oscilloscope and for input pulse measurement. After the initial measurement of output pulse width, the long fiber length may be cut back to a short length and the measurement repeated in order to obtain the effective input pulse width. The fiber is generally cut back to the lesser of 10 m or 1% of its original length. As an alternative to this cut-back technique, the insertion or substitution method similar to that used in fiber loss measurement can be employed. This method has the benefit of being nondestructive and only slightly less accurate than the cut-back technique.

The fiber dispersion is obtained from the two pulse width measurements which are taken at any convenient fraction of their amplitude. If $P_i(t)$ and $P_o(t)$ of Equation are assumed to have a Gaussian shape then Equation may be written in the form:

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

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

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

Where $\tau(3\ \text{dB})$,τ_i (3dB) and τ_o (3 dB) are measured in ns and L is the fiber length in Km. It must be noted that if a long length of fiber is cut back to a short length in order to take the input pulse width measurement, then *L* corresponds to the difference between the two fiber lengths in km.

Frequency domain measurement

Frequency domain measurement is the preferred method for acquiring the bandwidth of multimode optical fibers. This is because the baseband frequency response of the fiber may be obtained directly from these measurements using Equation without the need for any assumptions of Gaussian shape, or alternatively, the mathematically complex deconvolution of Equation which is necessary with measurements in the time domain. Thus the optical bandwidth of a multimode fiber is best obtained from frequency domain measurements.

One of two frequency domain measurement techniques is generally used. The first utilizes a similar pulsed source to that employed for the time domain measurements shown in Figure. However, the sampling oscilloscope is replaced by a spectrum analyzer which takes the Fourier transform of the pulse in the time domain and hence displays its constituent frequency components.

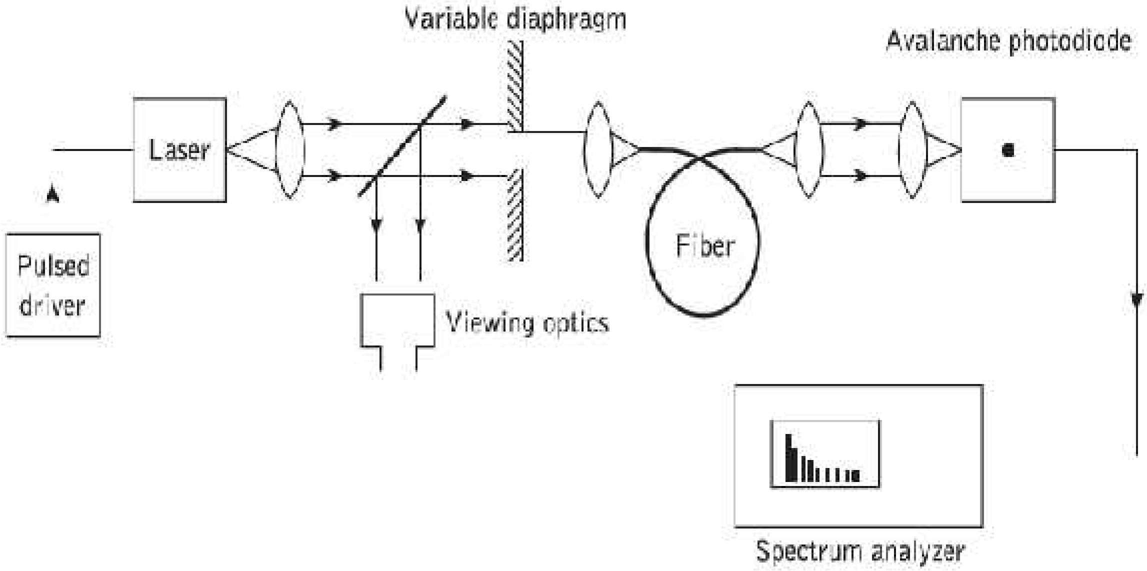


Figure Experimental setup for making fiber dispersion measurements in the frequency domain using a pulsed laser source

The experimental arrangement is illustrated in Figure. Comparison of the spectrum at the fiber output $P_o(w)$ with the spectrum at the fiber input $P_i(w)$ provides the baseband frequency response for the fiber under test where:

$$H(\omega)=\frac{\mathcal{P}_o(\omega)}{\mathcal{P}_i(\omega)}$$

The second technique involves launching a sinusoidally modulated optical signal at different selected frequencies using a sweep oscillator. Therefore the signal energy is concentrated in a very narrow frequency band in the baseband region, unlike the pulse measurement method where the signal energy is spread over the entire baseband region.

Fiber refractive index profile measurements

The refractive index profile of the fiber core plays an important role in characterizing the properties of optical fibers. It allows determination of the fiber's numerical aperture and the number of modes propagating within the fiber core, while largely defining any intermodal and/or profile dispersion caused by the fiber. Hence a detailed knowledge of the refractive index profile enables the impulse response of the fiber to be predicted.

Also, as the impulse response and consequently the information-carrying capacity of the fiber is strongly dependent on the refractive index profile, it is essential that the fiber manufacturer is able to produce particular profiles with great accuracy, especially in the case of graded index fibers (i.e. optimum profile). There is therefore a requirement for accurate measurement of the refractive index profile. These measurements may be performed using a number of different techniques each of which exhibit certain advantages and drawbacks.

Interferometric methods

Interference microscopes (e.g. Mach–Zehnder, Michelson) have been widely used to determine the refractive index profiles of optical fibers. The technique usually involves the preparation of a thin slice of fiber (slab method) which has both ends accurately polished to obtain square (to the fiber axes) and optically flat surfaces. The slab is often immersed in an index-matching fluid, and the assembly is examined with an interference microscope. Two major methods are then employed, using either a transmitted light interferometer or a reflected light interferometer.

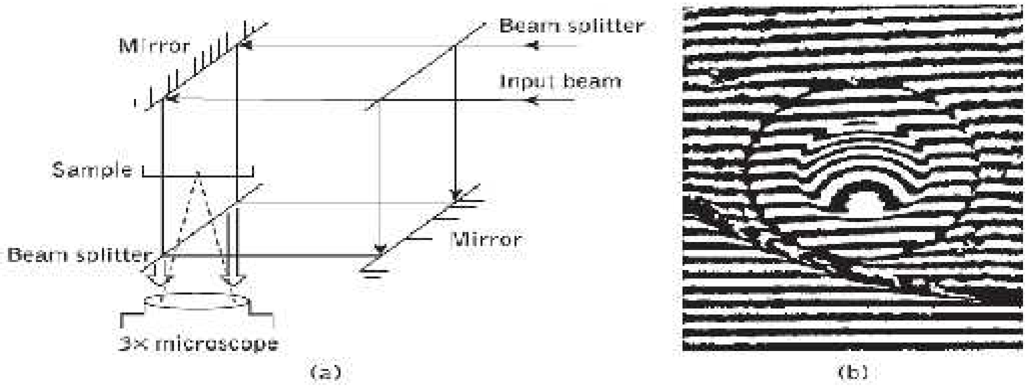


Figure (a) The principle of the Mach–Zehnder interferometer. (b) The interference fringe pattern obtained with an interference microscope from a graded index fiber

In both cases light from the microscope travels normal to the prepared fiber slice faces (parallel to the fiber axis), and differences in refractive index result in different optical path lengths. This situation is illustrated in the case of the Mach–Zehnder interferometer in Figure. When the phase of the incident light is compared with the phase of the emerging light, a field of parallel interference fringes is observed. The fringe displacements for the points within the fiber core are then measured using as reference the parallel fringes outside the fiber core (in the fiber cladding). The refractive index difference between a point in the fiber core (e.g. the core axis) and the cladding can be obtained from the fringe shift *q*, which corresponds to a number of fringe displacements.

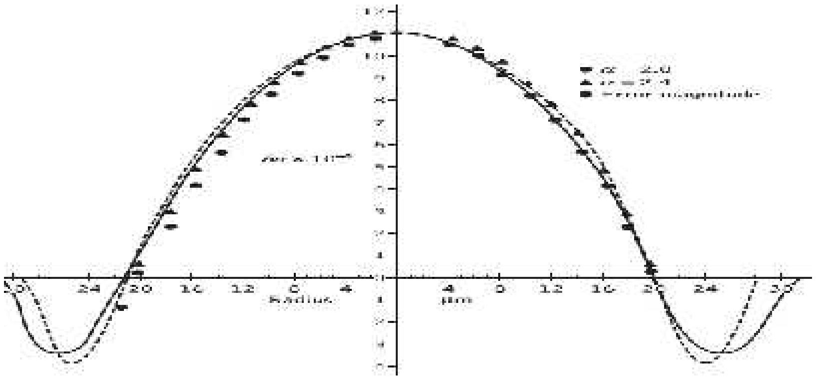


Figure The fiber refractive index profile computed from the interference pattern

This difference in refractive index is given by:

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

Where x is the thickness of the fiber slab and λ is the incident optical wavelength. The slab method gives an accurate measurement of the refractive index profile, although computation of the individual points is somewhat tedious unless an automated technique is used. Figure shows the refractive index profile obtained from the fringe pattern indicated in Figure

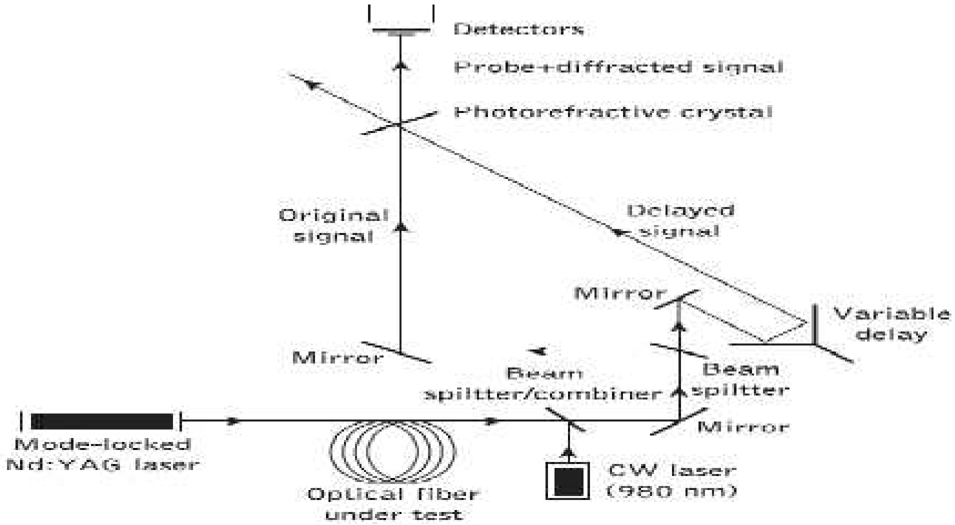


Figure Experimental setup for the measurement of the refractive index of silica fiber using the induced-grating autocorrelation function technique

Figure shows the experimental setup used to observe an IGA response using a nonlinear optical loop mirror interferometer. It consists of a laser source and a combination of optical lenses and mirrors where a beam splitter separates the signal creating the delayed path. The two optical signals (i.e. original and delayed signals) combine at a point where a photorefractive crystal is placed which is the mixing element employed in this method. Several crystalline material systems, known as photorefractive crystals, can be used to produce a diffraction grating in order to implement IGA. Photorefraction is however, an electro-optic phenomenon in which the local index of refraction is modified by spatial variations of the light intensity.

Near-field scanning method

The near-field scanning or transmitted near-field method utilizes the close resemblance that exists between the near-field intensity distribution and the refractive index profile, for a fiber with all the guided modes equally illuminated. It provides a reasonably straightforward and rapid method for acquiring the refractive index profile.

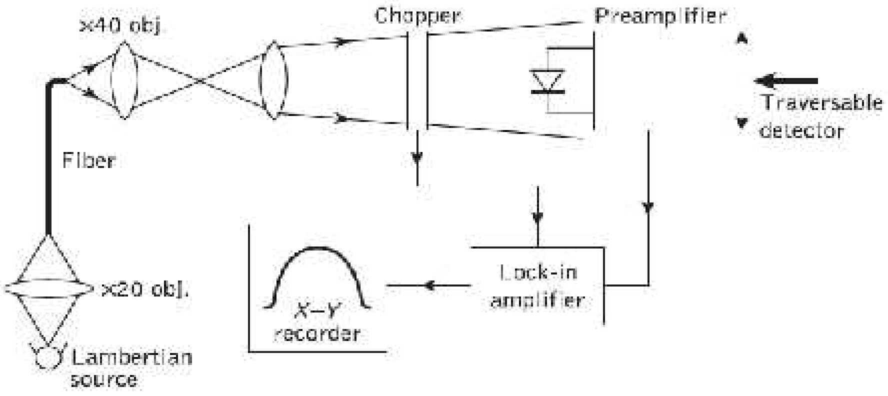


Figure Experimental setup for the near-field scanning measurement of the refractive index profile

When a diffuse Lambertian source (e.g. tungsten filament lamp or LED) is used to excite all the guided modes then the near-field optical power density at a radius r from the core axis $P_D(r)$ may be expressed as a fraction of the core axis near-field optical power density $P_D(0)$ following:

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

where $n_1(0)$ and $n_1(r)$ are the refractive indices at the core axis and at a distance r from the core axis respectively, $n2$ is the cladding refractive index and $C(r, z)$ is a correction factor. The correction factor which is incorporated to compensate for any leaky modes present in the short test fiber may be determined analytically.

The transmitted near-field approach is, however, not similarly recommended for single-mode fiber. The output from a Lambertian source is focused onto the end of the fiber using a microscope objective lens. A magnified image of the fiber output end is displayed in the plane of a small active area photodetector (e.g. silicon *p–i–n* photodiode). The photodetector which scans the field transversely receives amplification from the phase-sensitive combination of the optical chopper and lock-in amplifier. Hence the profile may be plotted directly on an *X–Y* recorder.

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

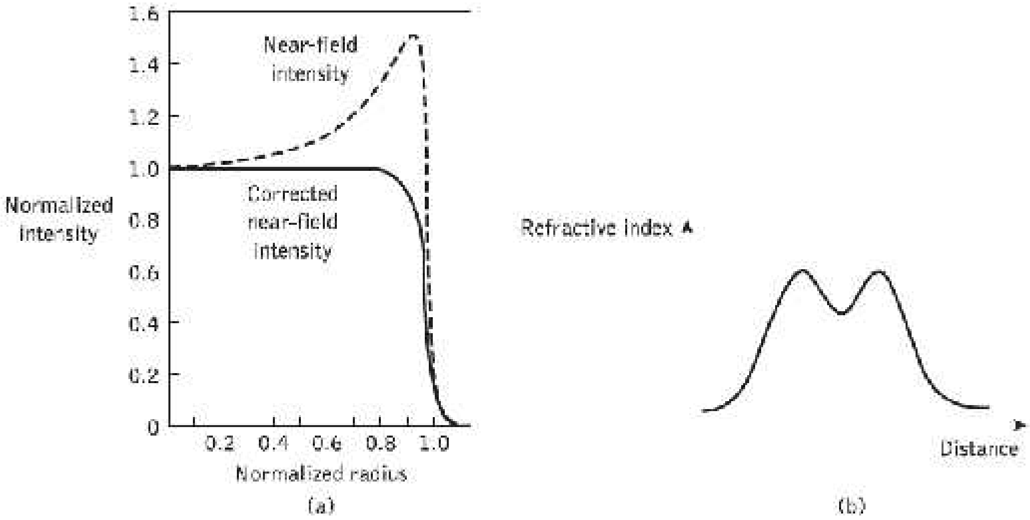


Figure (a) The refractive index profile of a step index fiber measured using the near-field scanning method, showing the near-field intensity and the corrected near field intensity. (b) The refractive index profile of a practical step index fiber measured by the near-field scanning method

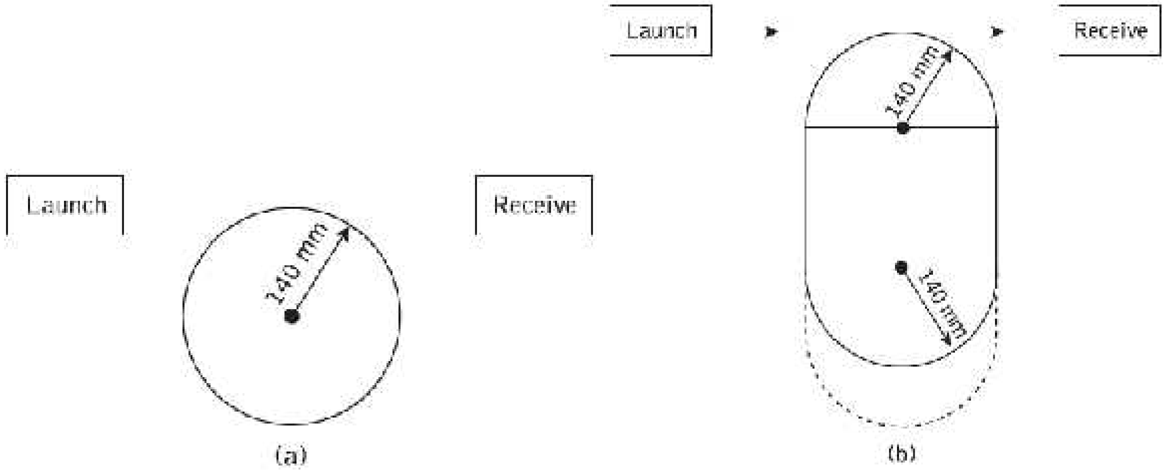
Fiber cutoff wavelength measurements

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

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

Where a is the core radius and $n1$ and $n2$ are the core peak and cladding indices respectively. It may be observed from Equation that operation at longer wavelengths yields fewer guided modes. Therefore it is clear that as the wavelength is increased, a growing number of modes are cutoff where the cutoff wavelength of a LP*lm* mode is the maximum wavelength for which the mode is guided by the fiber.

Usually the cutoff wavelength refers to the operation of single-mode fiber in that it is the cutoff wavelength of the LP11 mode (which has the longest cutoff wavelength) which makes the fiber single moded when the fiber diameter is reduced to 8 or 9 µm. Hence the cutoff wavelength of the LP11 is the shortest wavelength above which the fiber exhibits single-mode operation and it is therefore an important parameter to measure. The theoretical value of the cutoff wavelength can be determined from the fiber refractive index profile because of the large attenuation of the LP11 mode near cutoff. However, the parameter which is experimentally determined is called the effective cutoff wavelength, which is always smaller than the theoretical cutoff wavelength by as much as 100 to 200 nm. It is this effective cutoff wavelength which limits the wavelength region for which the fiber is 'effectively' single-mode.



(a) (b)

Figure Configurations for the measurement of uncabled fiber cutoff wavelength: (a) single turn; (b) split mandrell

In the bending-reference technique the power $P_s(\lambda)$ transmitted through the fiber sample in the configurations shown in Figure is measured as a function of wavelength. Thus the quantity $P_s(\lambda)$ corresponds to the total power, including launched higher order modes, of the ITU-T definition for cutoff wavelength. Then keeping the launch conditions fixed, at least one additional loop of sufficiently small radius (60 mm or less) is introduced into the test sample to act as a mode filter to suppress the secondary LP11 mode without attenuating the fundamental mode at the effective cutoff wavelength. In this case the smaller transmitted spectral power $P_b(\lambda)$ is measured which corresponds to the fundamental mode power referred to in the definition. The bend attenuation $a_b(\lambda$ comprising the level difference between the total power and the fundamental power is calculated as:

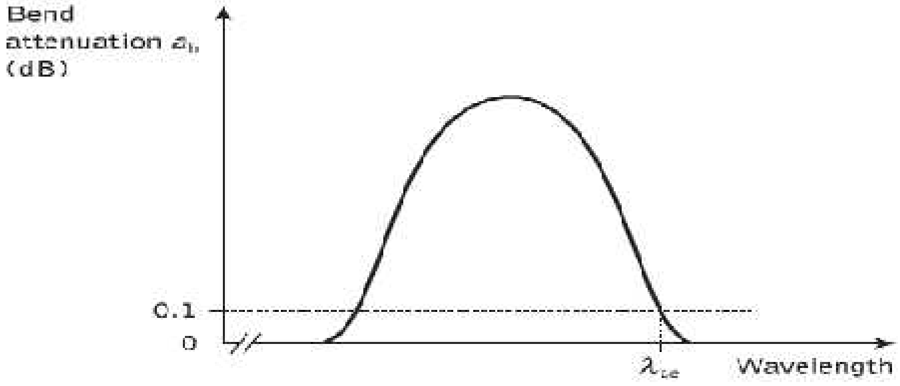


Figure Bend attenuation against wavelength in the bending method

The end attenuation characteristic exhibits a peak in the wavelength region where the radiation losses resulting from the small loop are much higher for the LP11 mode than for the LP01 fundamental mode, as illustrated in figure. It should be noted that the shorter wavelength side of the attenuation maximum corresponds to the LP11 mode, being well confined in the fiber core, and hence negligible loss is induced by the 60 mm diameter loop, whereas on the longer wavelength side the LP11 mode is not guided in the fiber and therefore, assuming that the loop diameter is large enough to avoid any curvature loss to the fundamental mode, there is also no increase in loss.

The relative attenuation $a_m(\lambda)$ or level difference between the powers launched into the multimode and single-mode fibers may be computed as:

$$a_m(\lambda) = 10 \log_{10} \frac{P_s(\lambda)}{P_m(\lambda)}$$

Fiber numerical aperture measurements

The numerical aperture is an important optical fiber parameter as it affects characteristics such as the light-gathering efficiency and the normalized frequency of the fiber (*V*). This in turn dictates the number of modes propagating within the fiber (also defining the single mode region) which has consequent effects on both the fiber dispersion (Intermodal) and, possibly, the fiber attenuation (Differential attenuation of modes). The numerical aperture (*NA*) is defined for a step index fiber as:

$$NA = \sin \theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}}$$

Where Θ_a is the maximum acceptance angle, n_1 is the core refractive index and n_2 is the cladding refractive index. Although equation may be employed with graded index fibers, the numerical aperture thus defined represents only the local *NA* of the fiber on its core axis (the numerical aperture for light incident at the fiber core axis). The graded profile creates a multitude of local *NA*s as the refractive index changes radially from the core axis.

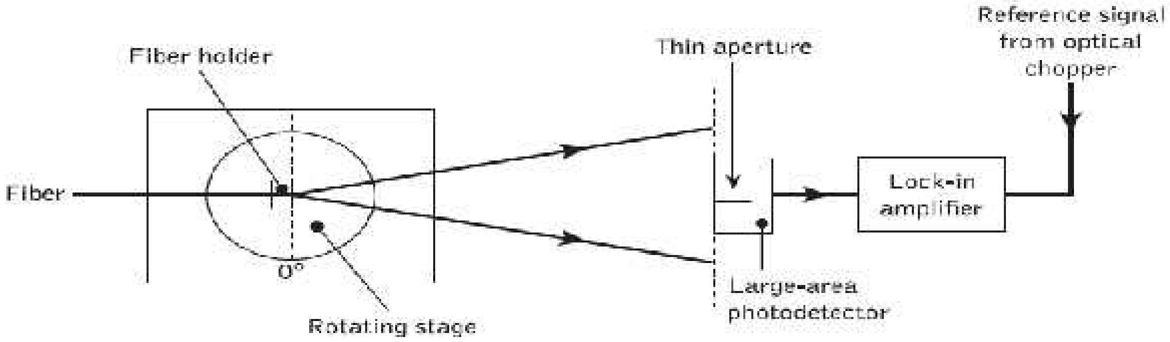


Figure Fiber numerical aperture measurement using a scanning photodetector and a rotating stage

It is assumed that the light is incident on the fiber end face from air with a refractive index (n_0) of unity. For the general case of a graded index fiber these local numerical apertures $NA(r)$ at different radial distances *r* from the core axis may be defined by:

$$NA(r) = \sin \theta_a(r) = (n_1^2(r) - n_2^2)^{\frac{1}{2}}$$

Therefore, calculations of numerical aperture from refractive index data are likely to be less accurate for graded index fibers than for step index fibers unless the complete refractive index profile is considered. The numerical aperture may be determined by calculation.

An example of an experimental arrangement with a rotating stage is shown in Figure. A 2m length of the graded index fiber has its faces prepared in order to ensure square smooth terminations.

The fiber output end is then positioned on the rotating stage with its end face parallel to the plane of the photodetector input, and so that its output is perpendicular to the axis of rotation. Light at a wavelength of 0.85 μm is launched into the fiber at all possible angles (overfilling the fiber) using an optical system similar to that used in the spot attenuation measurements.

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

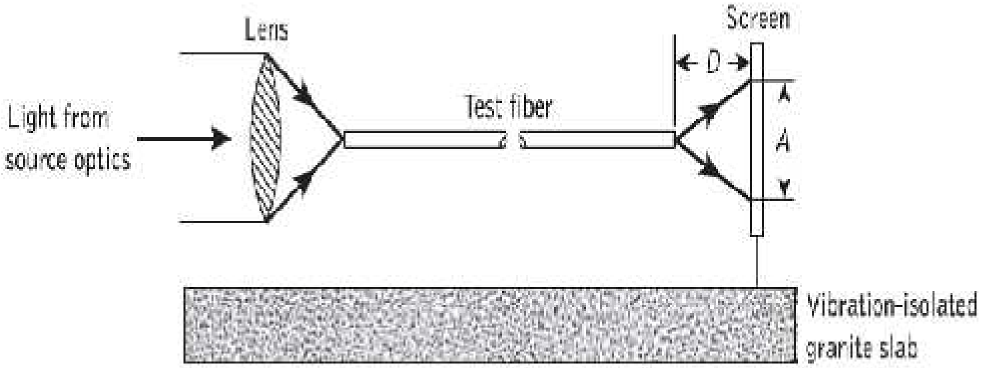


Figure Apparatus for trigonometric fiber numerical aperture measurement

Where the end prepared fiber is located on an optical base plate or slab. Again light is launched into the fiber under test over the full range of its numerical aperture, and the far field pattern from the fiber is displayed on a screen which is positioned a known distance *D* from the fiber output end face. The test fiber is then aligned so that the optical intensity on the screen is maximized. Finally, the pattern size on the screen *A* is measured using a calibrated vernier caliper. The numerical aperture can be obtained from simple trigonometrical relationships where

$$NA = \sin \theta_a = \frac{A/2}{[(A/2)^2 + D^2]^{\frac{1}{2}}} = \frac{A}{(A^2 + 4D^2)^{\frac{1}{2}}}$$

It must be noted that the accuracy of this measurement technique is dependent upon the visual assessment of the far-field pattern from the fiber. The above measurement techniques are generally employed with multimode fibers only, as the far-field patterns from single-mode fibers are affected by diffraction phenomena.

Fiber diameter measurements

Outer diameter

It is essential during the fiber manufacturing process (at the fiber drawing stage) that the fiber outer diameter (cladding diameter) is maintained constant to within 1%. Any diameter variations may cause excessive radiation losses and make accurate fiber–fiber connection difficult. Hence on-line diameter measurement systems are required which provide accuracy better than 0.3% at a measurement rate greater than 100 Hz (i.e. a typical fiber drawing velocity is 1 m/s). Use is therefore made of non contacting optical methods such as fiber image projection and scattering pattern analysis.

The most common on-line measurement technique uses fiber image projection (shadow method) and is illustrated in Figure. In this method a laser beam is swept at a constant velocity transversely across the fiber and a measurement is made of the time interval during which the fiber intercepts the beam and casts a shadow on a photodetector.

In the apparatus shown in Figure the beam from a laser operating at a wavelength of 0.6328 μm is collimated using two lenses (*G*1 and *G*2). It is then reflected off two mirrors (*M*1 and *M*2), the second of which (*M*2) is driven by a galvanometer which makes it rotate through a small angle at a constant angular velocity before returning to its original starting position. Therefore, the laser beam which is focused in the plane of the fiber by a lens (*G*3) is swept across the fiber by the oscillating mirror and is incident on the photodetector unless it is blocked by the fiber. The velocity d*s*/d*t* of the fiber shadow thus created at the photodetector is directly proportional to the mirror velocity following:

$$\frac{\mathrm{d}s}{\mathrm{d}t} = l\frac{\mathrm{d}\phi}{\mathrm{d}t}$$

Where l is the distance between the mirror and the photodetector. Furthermore, the shadow is registered by the photodetector as an electrical pulse of width W_e which is related to the fiber outer diameter d_o as:

$$d_o = W_e\frac{\mathrm{d}s}{\mathrm{d}t}$$

Thus the fiber outer diameter may be quickly determined and recorded on the printer. The measurement speed is largely dictated by the inertia of the mirror rotation and its accuracy by the rise time of the shadow pulse. Other on-line measurement methods, enabling faster diameter measurements, involve the analysis of forward or backward far-field patterns which are produced when a plane wave is incident transversely on the fiber. These techniques generally require measurement of the maxima in the center portion of the scattered pattern from which the diameter can be calculated after detailed mathematical analysis. They tend to give good accuracy (e.g. ±0.25 μm) even though the theory assumes a perfectly circular fiber cross-section. Also, for step index fibers the analysis allows determination of the core diameter, and core and cladding refractive indices.

Measurements of the fiber outer diameter after manufacture (off-line) may be performed using a micrometer or dial gage. These devices can give accuracies of the order of ±0.5 µm. Alternatively, off-line diameter measurements can be made with a microscope incorporating a suitable calibrated micrometer eyepiece

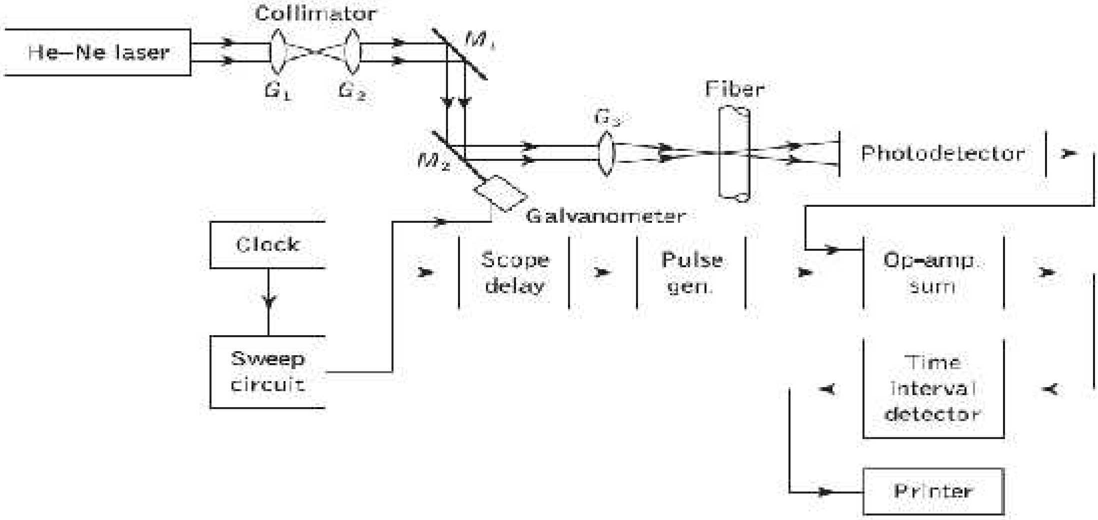


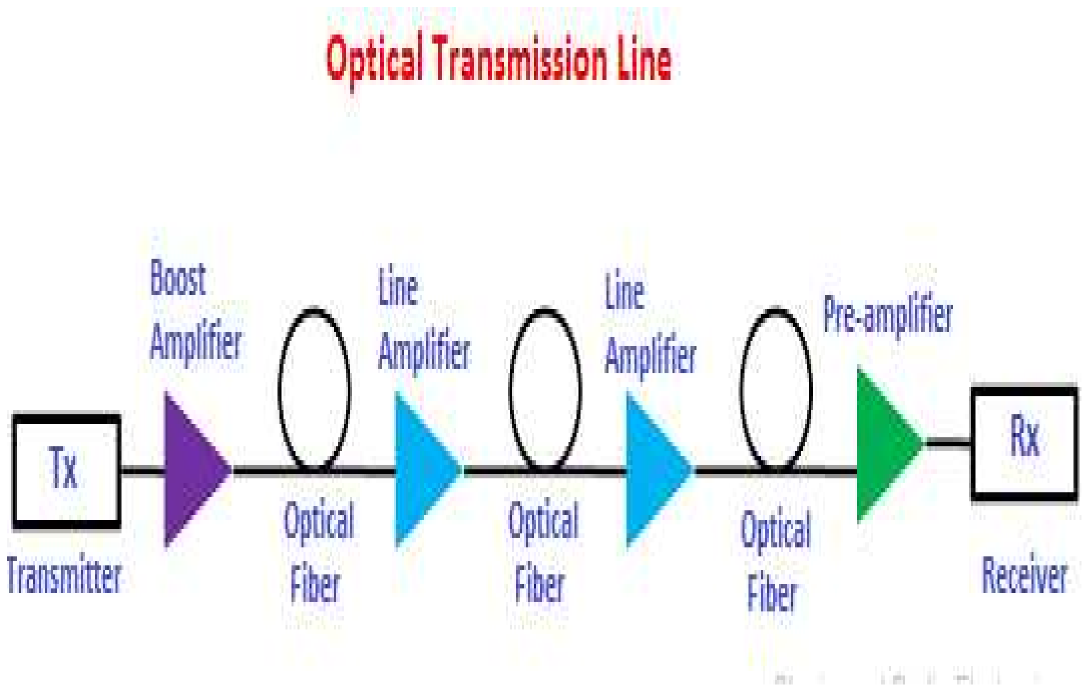
Figure the shadow method for the on-line measurement of the fiber outer diameter.

Core diameter

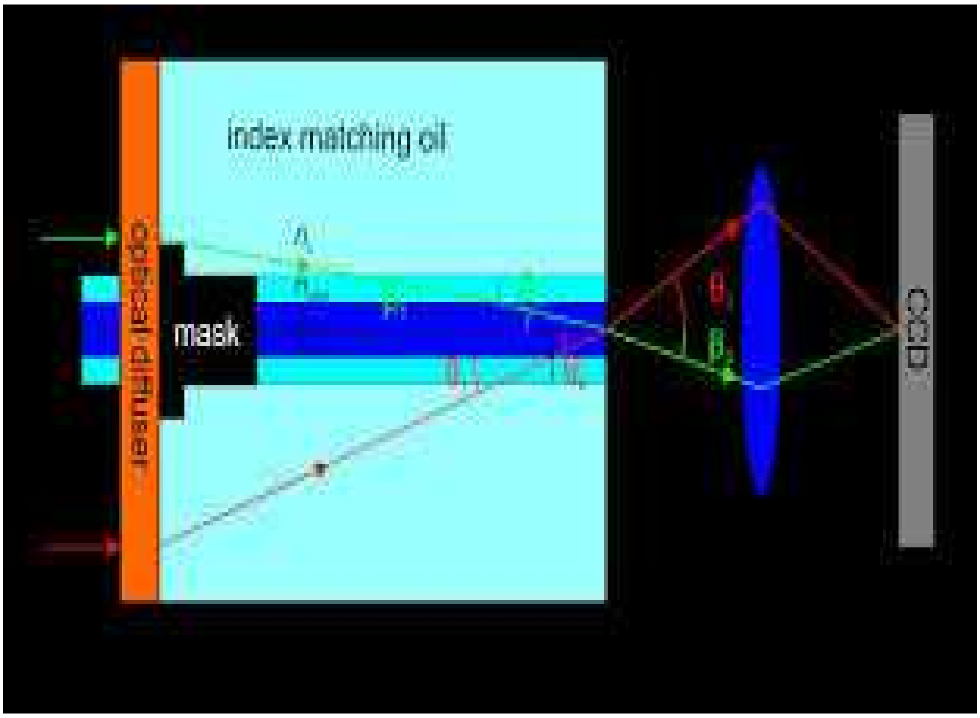
The core diameter for step index fibers is defined by the step change in the refractive index profile at the core–cladding interface. Therefore the techniques employed for determining the refractive index profile (interferometric, near-field scanning, refracted ray, etc.) may be utilized to measure the core diameter. Graded index fibers present a more difficult problem as, in general, there is a continuous transition between the core and the cladding.

In this case it is necessary to define the core as an area with a refractive index above a certain predetermined value if refractive index profile measurements are used to obtain the core diameter. Core diameter measurement is also possible from the near-field pattern of a suitably illuminated (all guided modes excited) fiber. The measurements may be taken using a microscope equipped with a micrometer eyepiece similar to that employed for off-line outer diameter measurements.

APPLICATIONS



Example of pre-amplifier in EDFA



Examples of 2Dimensional refractive index profiling of optical fibers

POST TEST-MCQ TYPE

1. Which refers to any spurious or undesired disturbances that mask the received signal in a communication system?
a) Attenuation
b) Noise
c) Dispersion
d) Bandwidth

2. How many types of noise are observed because of the spontaneous fluctuations in optical fiber communication systems?
a) One
b) Four
c) Two
d) Three

3.Which is caused due to thermal interaction between the free electrons and the vibrating ions in the conduction medium.
a) Thermal noise
b) Dark noise
c) Quantum noise
d) Gaussian noise

4. The minimum pulse energy needed to maintain a given bit-error-rate (BER) which any practical receiver must satisfy is known as
a) Minimal energy
b) Quantum limit
c) Point of reversed
d) Binary signaling

5. Which is used in the specification of optical detectors.
a) Noise equivalent power
b) Polarization
c) Sensitivity
d) Electron movement

6. Which of the following APDs are recognized for their high gain-bandwidth products?
a) GaAs
b) Alloy-made
c) Germanium
d) Silicon

7. How many circuits are present in an equivalent circuit for the digital optical fiber receiver?
a) Four
b) One
c) Three
d) Two

8. Which compensates for distortion of the signal due to the combined transmitter, medium and receiver characteristics?
a) Amplification
b) Distortion
c) Equalization
d) Dispersion

9. The phase frequency response of the system should be ____________ in order to minimize inter-symbol interference.
a) Non-Linear
b) Linear
c) More
d) Less

10. How many amplifier configurations are frequently used in optional fiber communication receivers?
a) One
b) Two
c) Three
d) Four

12. The major advantage of the trans-impedance configuration over the high-impedance front end is
a) Greater bandwidth
b) Less bandwidth
c) Greater dynamic range
d) Less dynamic range

13. The trans-impedance front end configuration operates as a __________ with negative feedback.
a) Current mode amplifier
b) Voltage amplifier
c) Attenuator
d) Resonator

14. Which is the lowest noise amplifier device?
a) Silicon FET
b) Amplifier-A
c) Attenuator
d) Resonator-B

15. FET device has extremely high input impedance greater than
a) 10^7 Ohms and less than 10^8
b) 10^6 Ohms and less than 10^7
c) 10^{14} Ohms
d) 10^{23} Ohms

16. High-performance microwave FETs are fabricated from
a) Silicon
b) Germanium
c) Gallium arsenide
d) Zinc

17. Which receiver can be fabricated using PIN-FET hybrid approach?
a) Trans-impedance front end receiver
b) Gallium arsenide receiver
c) High-impedance front-end
d) Low-impedance front-end

18. What is usually required by FETs to optimize the figure of merit?
a) Attenuation of barrier
b) Matching with the depletion region
c) Dispersion of the gate region
d) Matching with the detector

19. A technique used for determining the total fiber attenuation per unit length is ________ method.
a) Frank
b) Cut-off
c) cut-back
d) Erlangen

20. The system designer finds greatest interest in the
a) Overall fiber attenuation
b) Fiber dispersion
c) Latitude of the fiber
d) Durability

21. How many parameters are usually worked upon by the measurement techniques in attenuation?
a) Three
b) Two
c) One
d) Five

22. What type of light source is usually present in the cut-back method?
a) Tungsten or xenon
b) LED
c) Laser
d) Photo-sensor

23. The device used to remove any scattered optical power from the core is
a) Mode setup terminator
b) Nodal spectrum
c) Mode stripper
d) Attenuator

24. What is the unit of measurement of the optical attenuation per unit length?
a) dB-km
b) dB/km
c) km/dB
d) V

25. What are used to allow measurements at a selection of different wavelengths?
a) Diaphragms
b) Spot attenuators
c) Belts
d) Interference filters

26. Which technology is used by the backscatter measurement method?
a) Refraction
b) Francis flat recovery
c) Optical time domain reflectometry
d) Optical frequency

27. Which measurements checks the impurity level in the manufacturing process?
a) Material reflectometry
b) Material absorption loss
c) Material attenuation loss
d) Calorimetric loss

28. Which removes the light propagating in the cladding?
a) Cladding mode strippers
b) Core strippers
c) Mode enhancers
d) Attenuators

29. Which measurements give an indication of the distortion to the optical signals as they propagate down optical fibers?
a) Attenuation
b) Dispersion
c) Encapsulation
d) Frequency

30. The measurement of dispersion allows the **_________** of the fiber to be determined.
a) Capacity
b) Frequency
c) Bandwidth
d) Power

31. How many types of mechanisms are present which produce dispersion in optical fibers?
a) Three
b) Two
c) One
d) Four

32. Intermodal dispersion is nonexistent in ________ fibers.
a) Multimode
b) Single mode
c) Step index- multimode
d) Al-GU

33. In the single mode fibers, the dominant dispersion mechanism is
a) Intermodal dispersion
b) Frequency distribution
c) Material dispersion
d) Intra-modal dispersion

34. How many domains support the measurements of fiber dispersion?
a) One
b) Three
c) Four
d) Two

35. The time domain dispersion measurement setup involves _____________ as the photo detector.
a) Avalanche photodiode
b) Oscilloscope
c) Circulator
d) Gyrator

36. The detailed knowledge of the refractive index profile predicts the __________ of the fiber.
a) Nodal response
b) Variation in frequency
c) Impulse response
d) Amplitude

37. Which of the fiber is strongly dependent on the refractive index profile?
a) Amplitude
b) Tuning frequency
c) Diameter
d) Information carrying capacity

38. What is required in case of graded index fibers?
a) High amplitude
b) High frequency
c) High impulse response
d) Optimum profile

39. Which of the following have been widely used to determine the refractive index profiles of optical fibers?
a) Interference microscopes
b) Gyro meters
c) Mode-diameter device
d) Tunable microscopes

40. Which of the following is the main drawback of the slab technique?
a) Efficiency
b) Amplitude
c) Time required
d) Accuracy

41. What does ‘a’ stands for in the given equation?
$M_g=(\pi a/\lambda)^2(n_1^2 - n_2^2)$
a) Radius of the core
b) Constant
c) Coefficient of refraction
d) Density

42. What is the name of the test used to determine the efficient values of the effective cutoff wavelength?
a) Round robin test
b) Mandarin test
c) Hough Werner test
d) Fulton test
43. How many bend effects are produced in the fiber?
a) One
b) Three
c) Two
d) Four

44. Which method is the most commonly used method for the determination of the fiber refractive index profile?
a) Refracted near-field method
b) Bending-reference
c) Power step method
d) Alternative test method
45. The numerical aperture for a step index fiber is sine angle of the
a) Efficient angle
b) Aperture
c) Acceptance angle
d) Attenuation

46. Far field pattern measurements with regard to multimode fibers are dependent on the _____________ of the fiber.
a) Amplitude
b) Frequency
c) Diameter
d) Length

47. Which of the following is a non-contacting optical method of on-line diameter measurement?
a) Brussels’s method
b) Velocity differentiator method
c) Photo detector method
d) Image projection method

48. Which affects both the fiber attenuation and dispersion?
a) Refractive index
b) Micro-bending
c) Connectors
d) Splices

49. Which of the following is not included in the optical fiber link measurement test?
a) Attenuation measurement
b) Dispersion measurement
c) Splice loss measurement
d) Receiver sensitivity

50. The handheld optical power meter has a measurement accuracy of ________
a) 0.01 dB
b) 0.25 dB
c) 0.8 dB
d) 1 dB

51. Which may be used for measurement of the absolute optical attenuation on a fiber link?
a) Silicon photodiodes
b) InGaAsP photodiodes
c) Optical power meters
d) Gyrators

52. During the fiber drawing process, the fiber outer diameter is maintained constant to within
a) 2%
b) 1%
c) 5%
d) 10%

53. What is the minimum value of accuracy in diameter is needed to avoid radiation losses in the fiber?
a) 0.1%
b) 0.2%
c) 0.3%
d) 0.03%

54. Which of the following is a non-contacting optical method of on-line diameter measurement?
a) Brussels’s method
b) Velocity differentiator method
c) Photo detector method
d) Image projection method

CONCLUSION

In this unit, the characteristics of fiber optic receivers were discussed. The Fiber Attenuation measurements, Dispersion measurements, Fiber Refractive index profile measurements, Fiber cut- off Wave length Measurements, Fiber Numerical Aperture Measurements, Fiber diameter measurements and their techniques were learnt.

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ASSIGNMENT

1. With diagram explain the measurement of Cutoff wavelength of optical fiber?
2. With diagram explain the measurement of numerical aperture of a fiber and measurement of refractive index fiber?
3. Explain detail in fiber attenuation measurement and Dispersion measurements.
4. Explain the error sources and device the Probability of error for fiber optic system?
5. Explain the fiber optic receiver operation?
6. Write short notes on quantum limit?

AIM & OBJECTIVES

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

PRE TEST-MCQ TYPE

1. The network structure formed due to the interconnectivity patterns is known as a
a) Network
b) Struck
c) Topology
d) D-pattern

2. In the ___________ topology, the data generally circulates bi-directionally.
a) Mesh
b) Bus
c) Star
d) Ring

3. The ring and star topologies are combined in a ________ configuration.
a) Mesh
b) Fringe
c) Data
d) Singular

4. Packet switching is also called as
a) Frame switching
b) Cell switching
c) Trans-switching
d) Buffer switching

5. A ________________ is a series of logical connections between the source and destination nodes.
a) Cell circuit
b) Attenuation circuit
c) Virtual circuit
d) Switched network

UNIT V OPTICAL NETWORKS AND SYSTEM TRANSMISSION

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

THEORY

Introduction

SONET/SDH

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

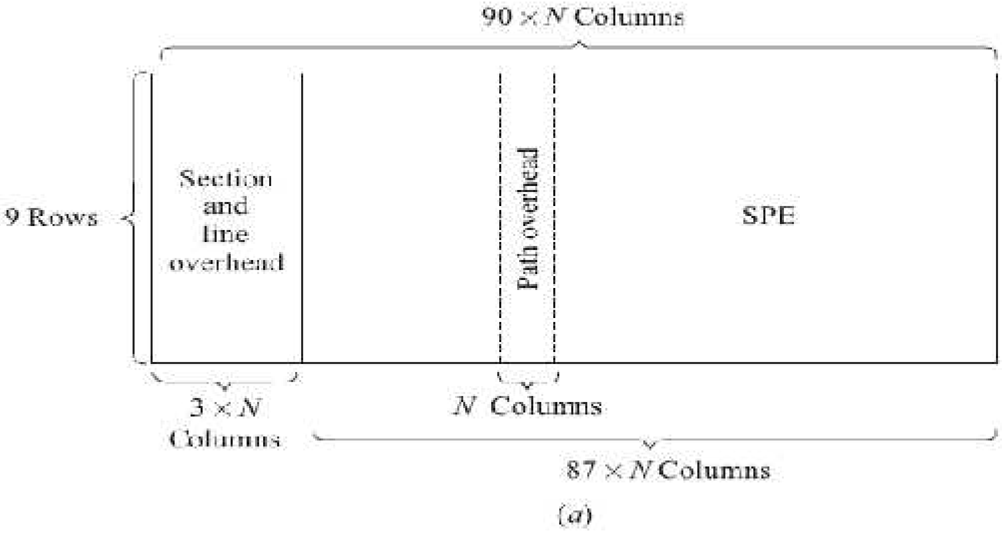


Figure Basic formats of an STS-N SONET frame

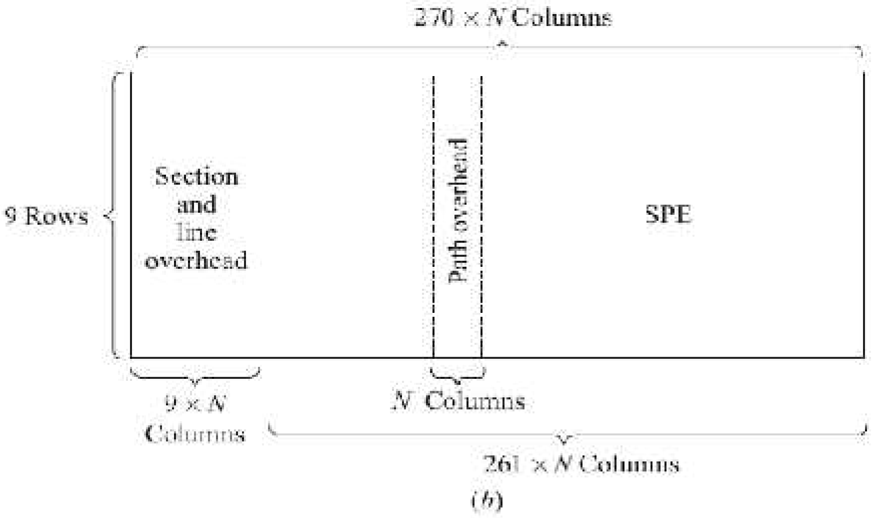


Figure Basic formats of an STM-N SDH frame

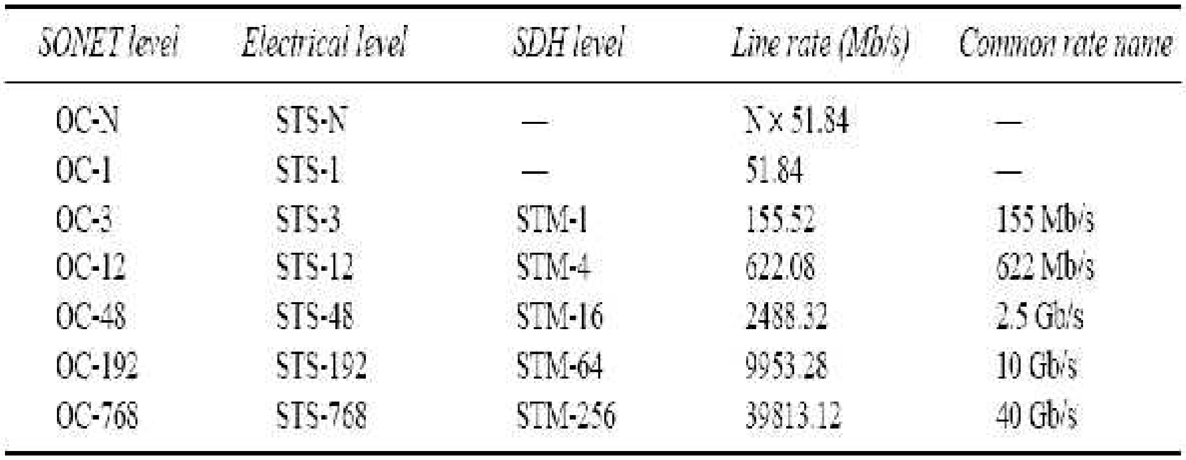
Common values of OC-N and STM-N:

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

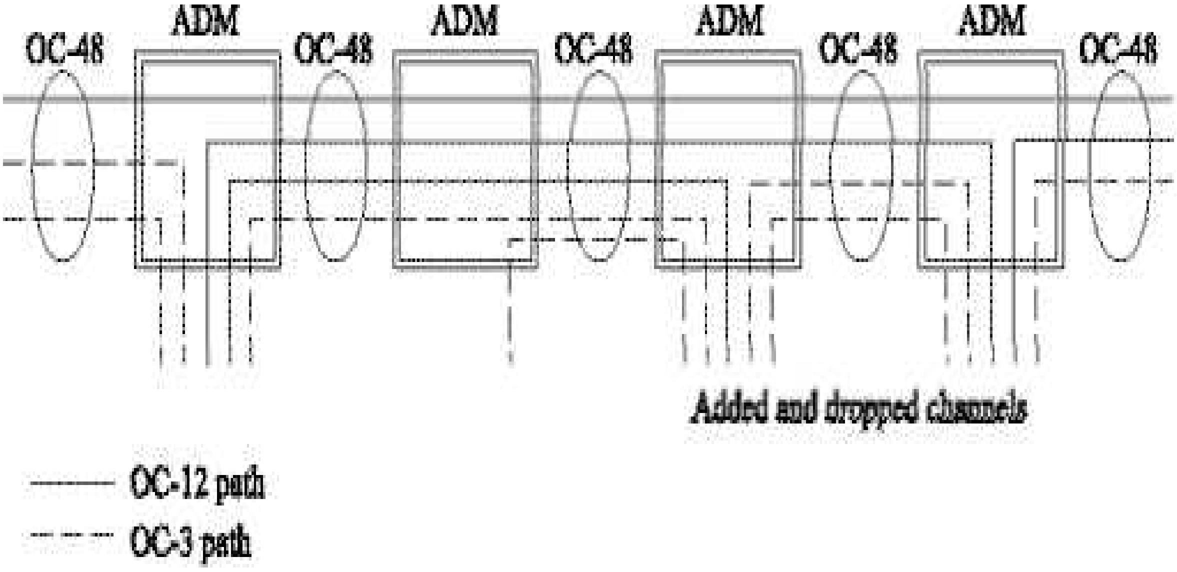
SONET Add Drop Multiplexers:

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

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



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



SONET/SDH Rings:

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

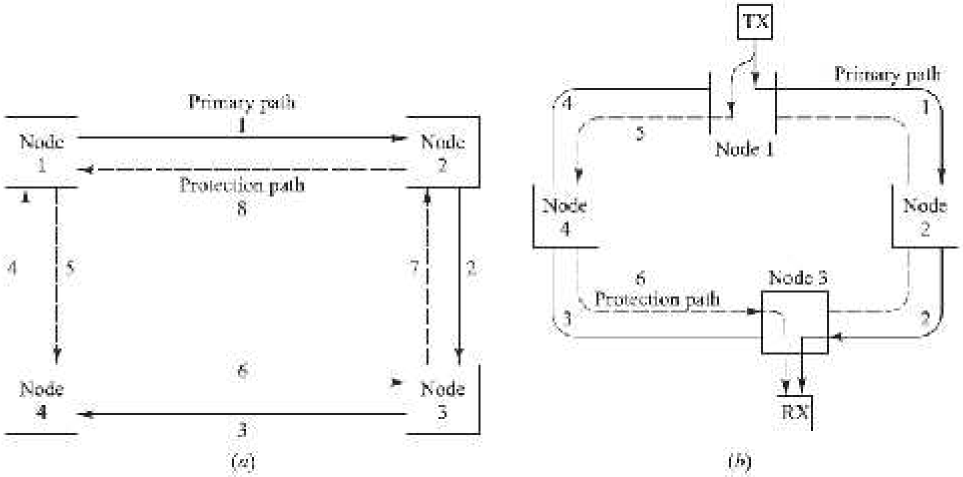
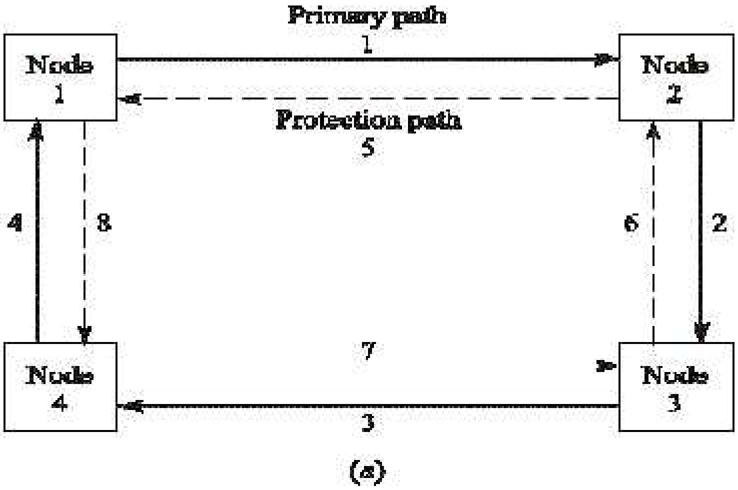


Figure Generic 2-fiber UPSR with a counter-rotating protection path

2-Fiber UPSR Basics:



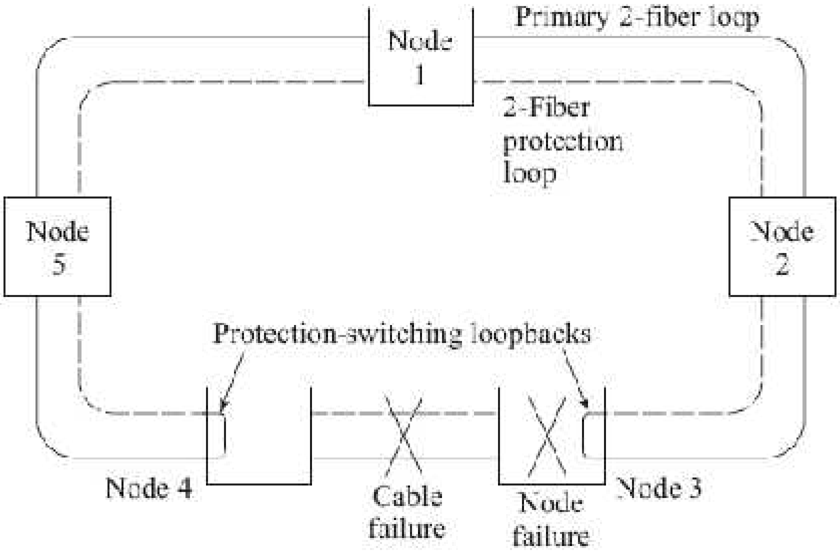
Ex: Total capacity OC-12 may be divided to four OC-3 streams, the OC-3 is called a path here

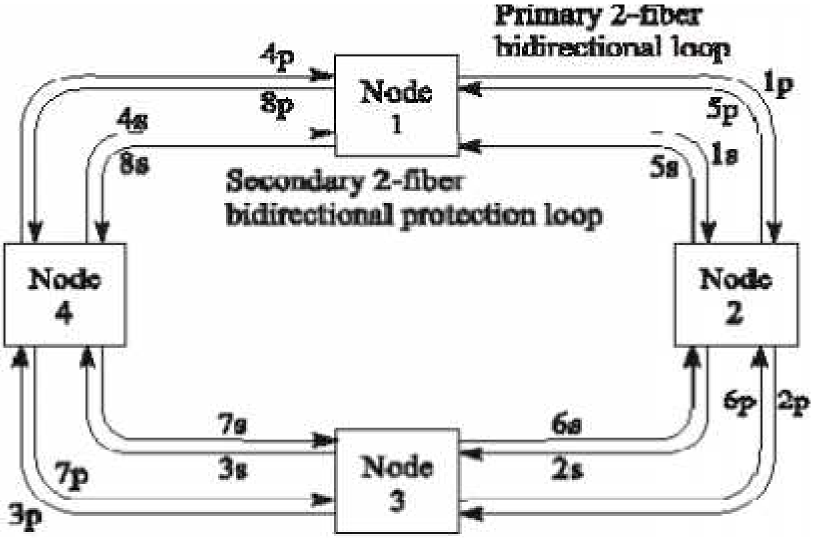
2-Fiber UPSR Protection:

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

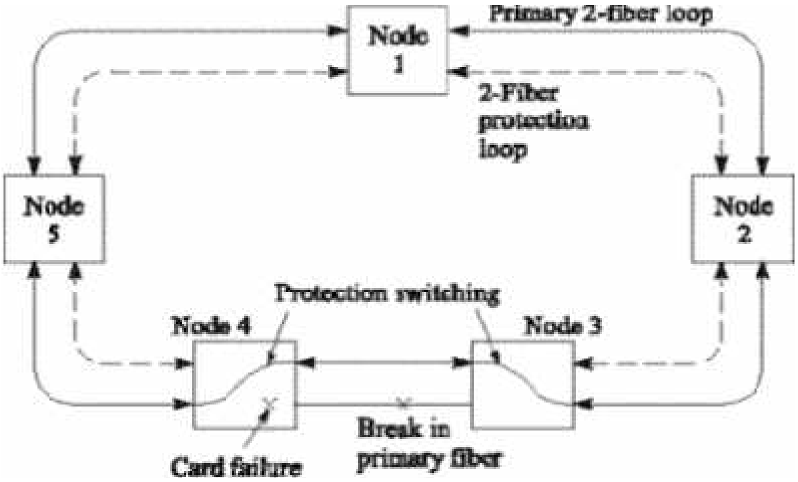
4-Fiber BLSR Basics:

Node 1 3; 1p, 2p Node3 1;3p, 4p



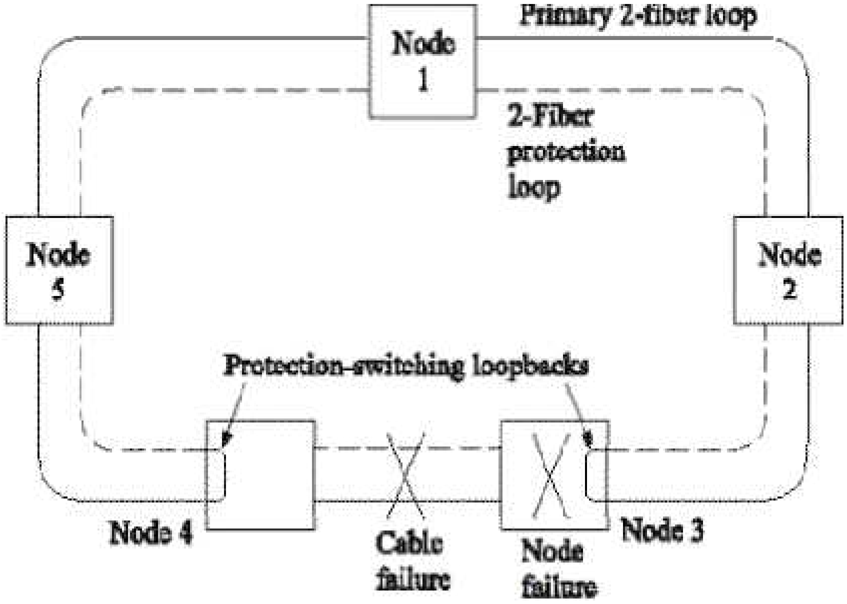


BLSR Fiber-Fault Reconfiguration:



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

BLSR Node-Fault Reconfiguration



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

BLSR Recovery from Failure Modes:

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

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

Broadcast and Select WDM Networks

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

Two categories of broadcast and select WDM networks

1. Single hop networks

2. Multihop networks

Broadcast and select single hop networks

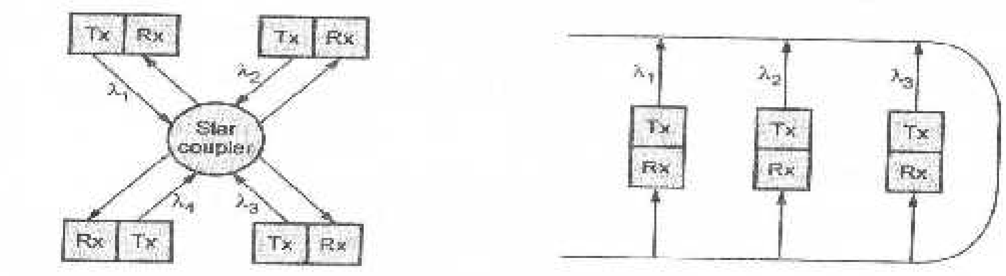


Fig: star configuration and bus configuration

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

Two physical configurations: star and bus

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

Passive star topology is attractive

- No tapping or insertion loss

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

- Simple network architecture

- Protocol transparent

Disadvantages

- It needs rapidly tunable lasers

Broadcast and select multihop networks

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

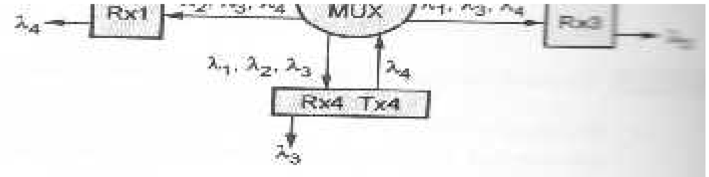


Figure multihop broad cast and select networks

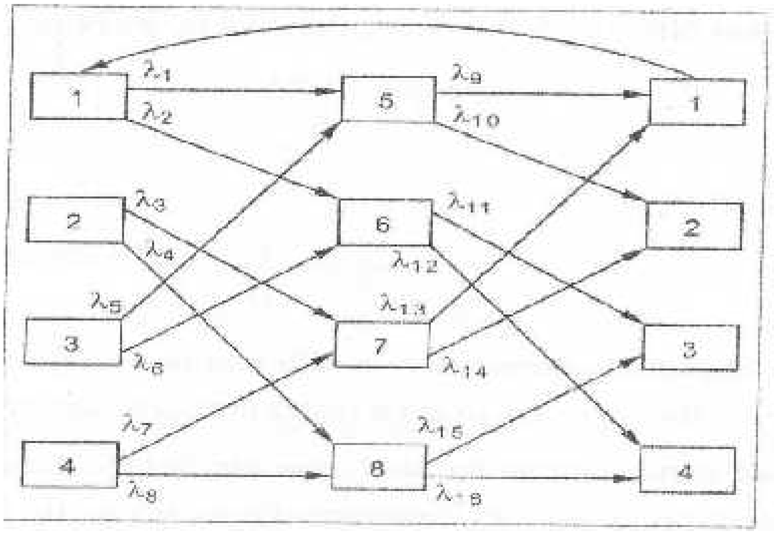


Figure logical interconnection pattern and wavelength assignment of a(p,) = (2,2) shuffle net

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

Shuffle net Multi hop network

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

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

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

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

Advantages of multihop networks

1. No packet collision within the network

2. Rapidly tunable lasers are not required

Disadvantages

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

Wavelength Routed Networks

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

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

To reduce this wavelength continuity constraint is to switch the wavelength channel at node 2 by converting the incoming wavelength λ2 to λ1 (which is available between nodes 2 and 3) to enable a link between node 2 and 3 to be established. The newly set up path uses two wavelength stages (i.e. two hops) to interconnect nodes 1 and 3. Such networks which employ wavelength conversion devices (or switches) are known as wavelength convertible networks. Three different WDM network architectures employing the wavelength conversion function are Full wavelength conversion, where each network link utilizes a dedicated wavelength converter, is depicted in Figure. All the wavelength channels at the output port of the optical switch will be converted into their compliant wavelength channel by the appropriate wavelength converter (WC).

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

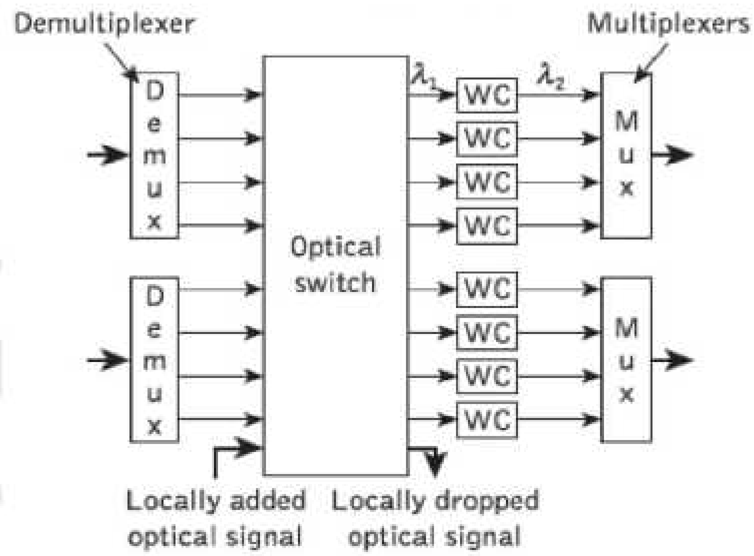


Figure Wavelength convertible routing network architectures: full or rededicated wavelength converters;

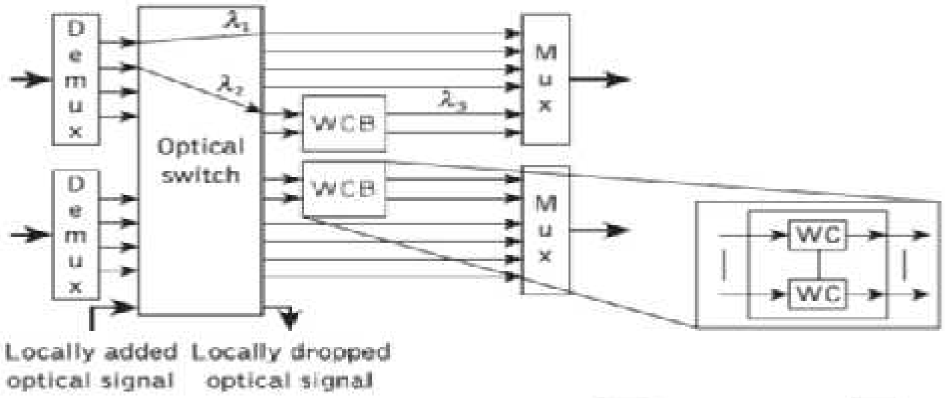


Figure Wavelength convertible routing network architectures: shared per link

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

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

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

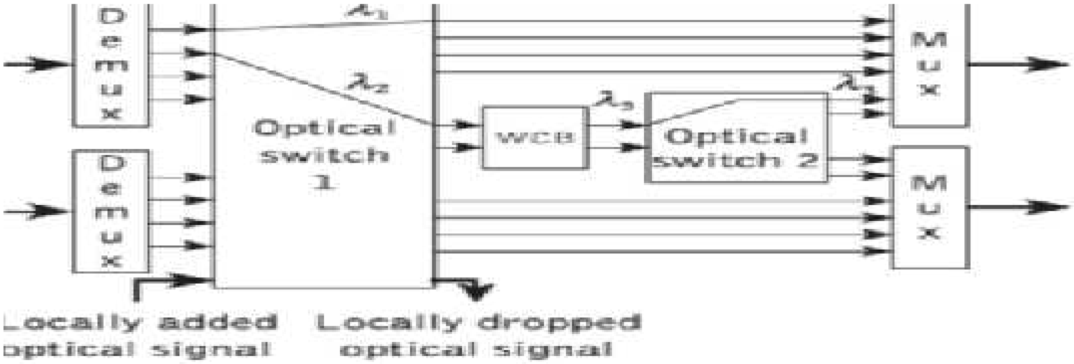


Figure wavelength routing and selection of a path

Non linear effects on Network performance

There are two categories of nonlinear effects.

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

Stimulated Raman scattering

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

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

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

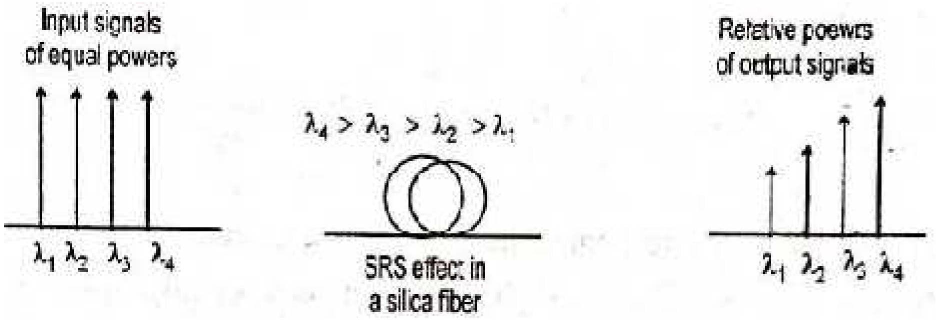


Figure SRS generates scattered light at a longer wavelength, thereby decreasing the power in the pump wavelength signal.

Stimulated Brillouin scattering

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

given by $V_B = 2nV_s / \lambda$

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

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

Self-Phase Modulation (SPM)

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

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

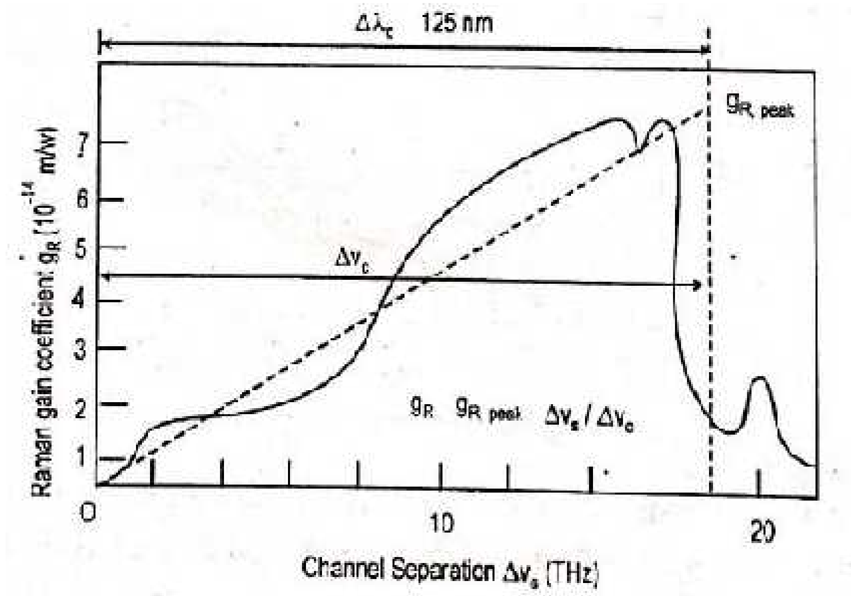


Figure Wavelength Channel separation

Four-wave mixing

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

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

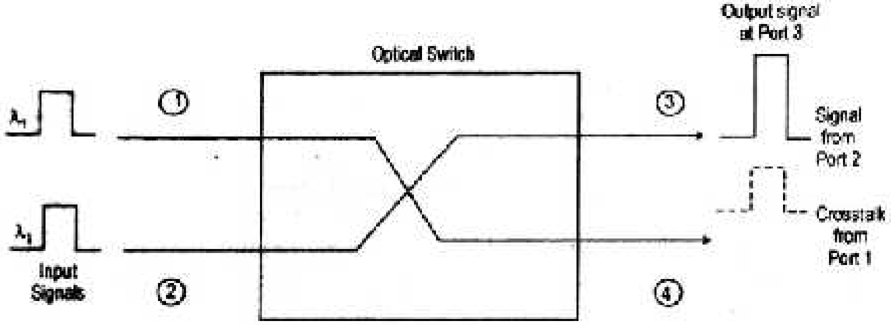


Figure Origin of interchannel crosstalk

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

$2V_1 – V_2$ and $2V_2 – V_1$

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

LINK POWER BUDGET:

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

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

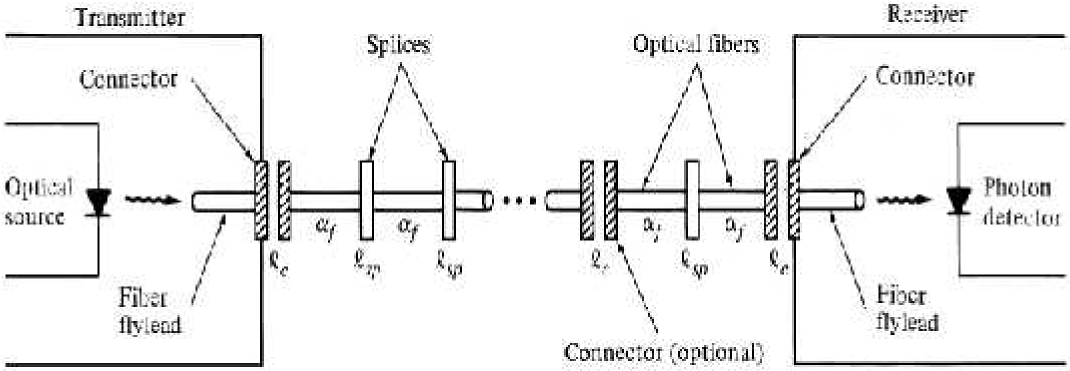


Figure Link power budget

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

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

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

Where, L is transmission distance.

Rise Time Budget

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

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

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

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

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

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

Receiver rise time (trx) Where,

Rise time due to modal dispersion is given as

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

Where,

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

q Is a parameter ranging between 0.5 and 1.

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

B_0 is bandwidth of 1 km length fiber

Rise time due to group velocity dispersion is

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

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

Receiver front end rise-time in nanoseconds is

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

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

Equation can be written as

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

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

WDM

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

NEED OF WDM

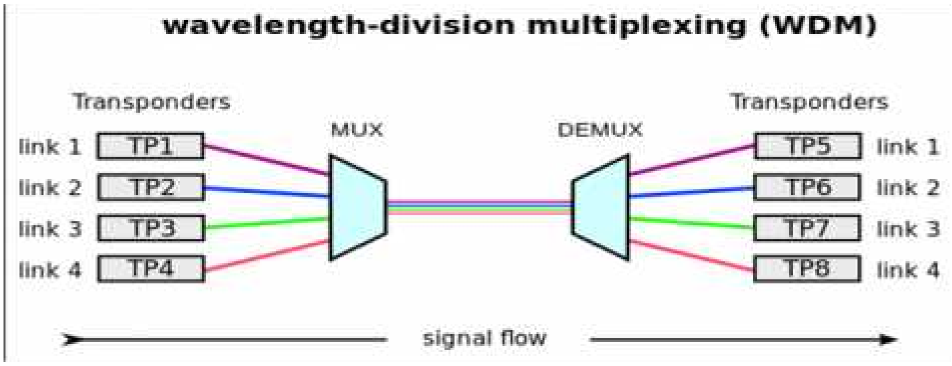
Due to the rapid growth in telecommunication links, high capacity and faster data transmission rates over farther distances are required. To meet these demands, network managers are relying more and more on fiber optics. Typically, there are three methods for expanding capacity: installing more cables,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

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

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

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

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



CWDM VS DWDM

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

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

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

OPERATIONAL PRINCIPLES OF WDM

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

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

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

WDM Operating Regions

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

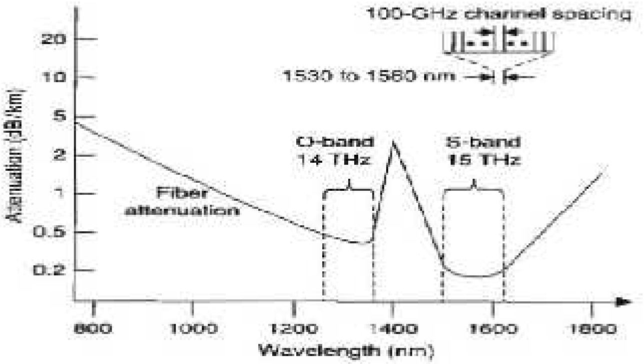


Figure Generic representation of attenuation of light in a silica fiber as a function of wavelength

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

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

Where the frequency deviation corresponds to wavelength deviation around the wavelength

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

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

Generic WDM Link

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

The transmitting side has a series of independently modulated fixed-wavelength light sources, 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.

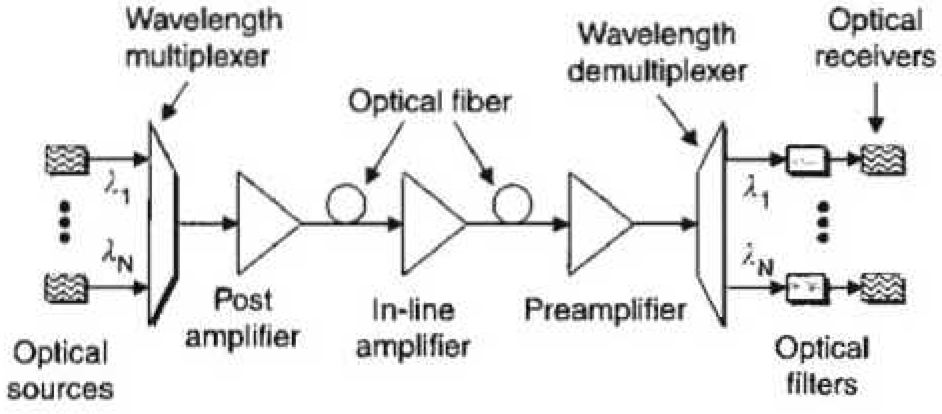


Figure Implementation of a simple WDM link

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

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

Wavelength Division Multiplexing (WDM)

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

Features of WDM

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

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

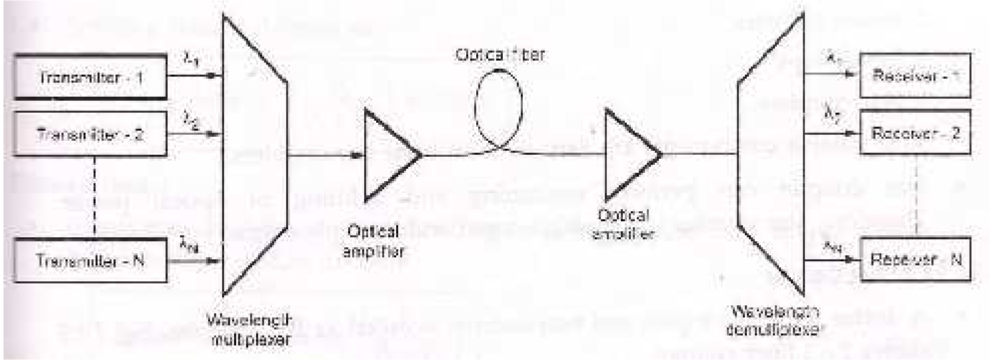


Figure WDM scheme

Passive Components

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

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

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

Dense Wavelength Division Multiplexing (DWDM)

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

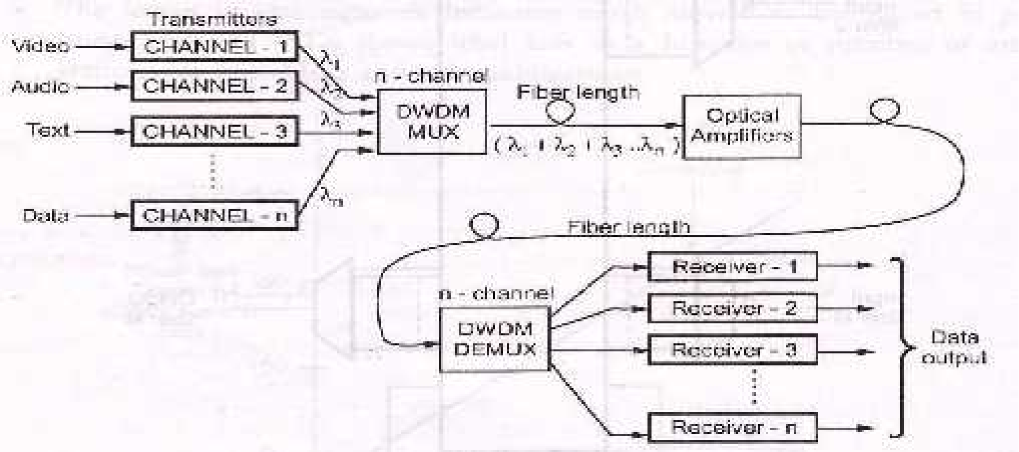


Figure DWDM System

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

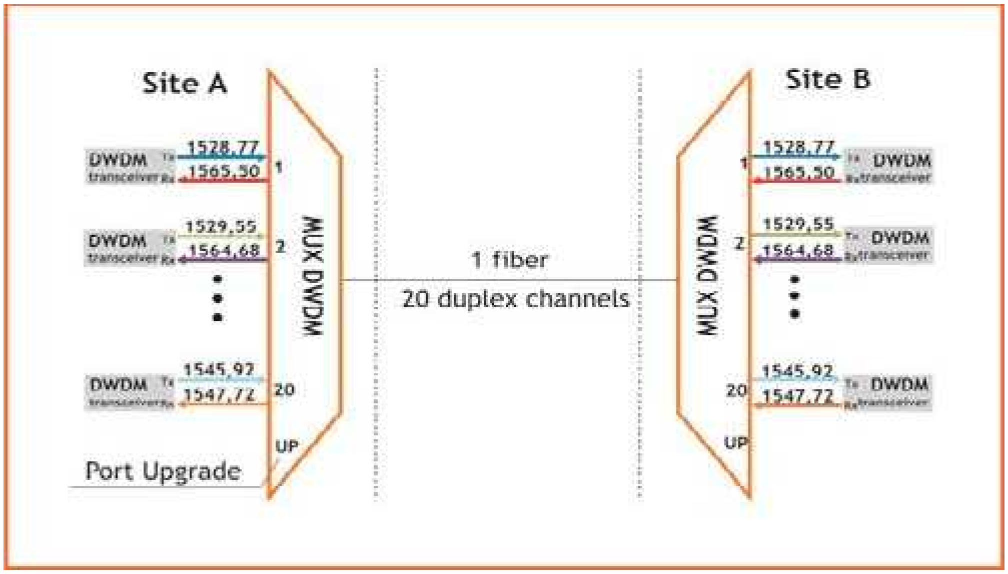
DWDW is short for dense wavelength division multiplexing. It is an optical multiplexing technology used to increase bandwidth over existing fiber networks. DWDM works by combining and transmitting multiple signals simultaneously at different wavelengths on the same fiber. It has revolutionized the transmission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

Passive DWDM

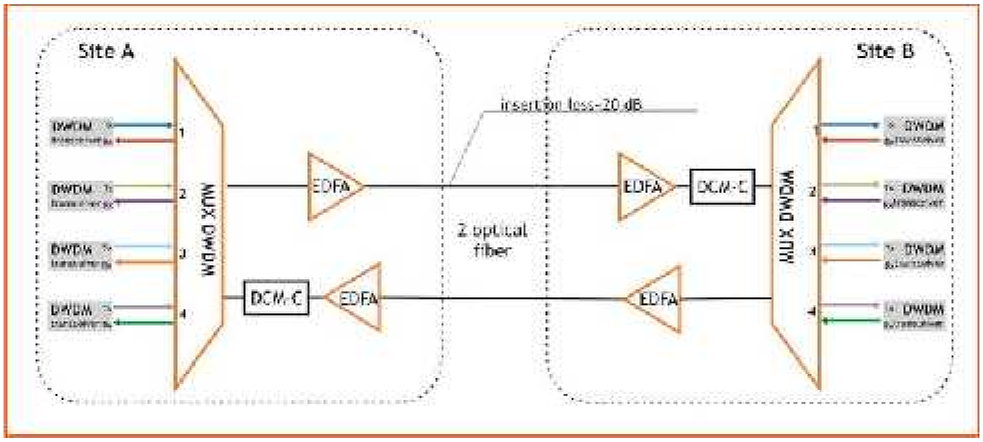
Passive DWDM systems have no active components. The line functions only due to the optical budget of transceivers used. No optical signal amplifiers and dispersion compensators are used. Passive DWDM systems have a high channel capacity and potential for expansion, but the transmission distance is limited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

Active DWDM

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



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



WDM multiplexer for DWDM communications

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

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

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

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

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

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

Erbium-Doped Fiber Amplifiers

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

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

Pumping Requirements

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

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

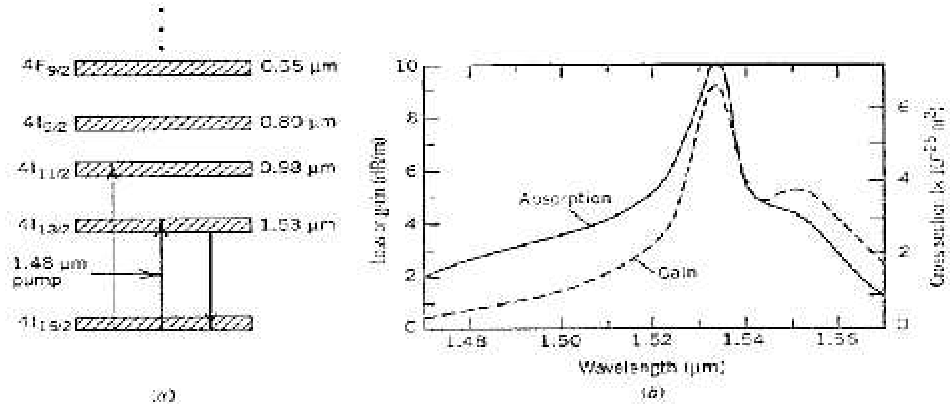


Figure (a) Energy-level diagram of erbium ions in silica fibers; (b) absorption and gain spectra of an EDFA whose core was co doped with germania

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

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

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

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

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

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

Multichannel Amplification

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

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

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

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

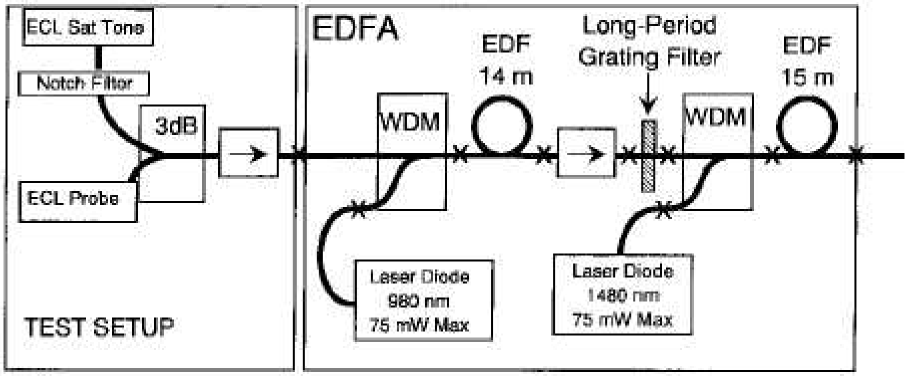


Figure Schematic of an EDFA designed to provide uniform gain over the 1530–1570- nm bandwidth using an optical filter containing several long-period fiber gratings. The two stage design helps to reduce the noise level.

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

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

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

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

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

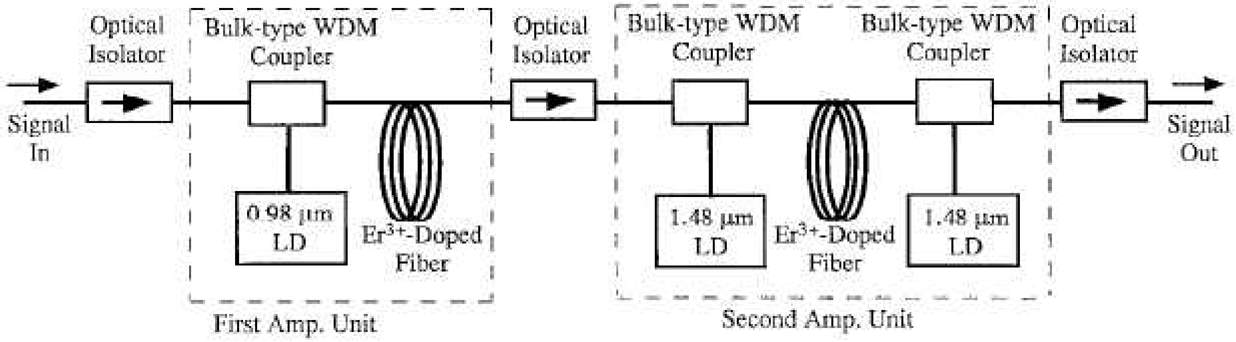


Figure Schematic of an L-band EDFA providing uniform gain over the 1570–1610-nm bandwidth with a two-stage design

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

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

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

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

Optical CDMA

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

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

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

Direct-sequence or temporal coding optical CDMA systems

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

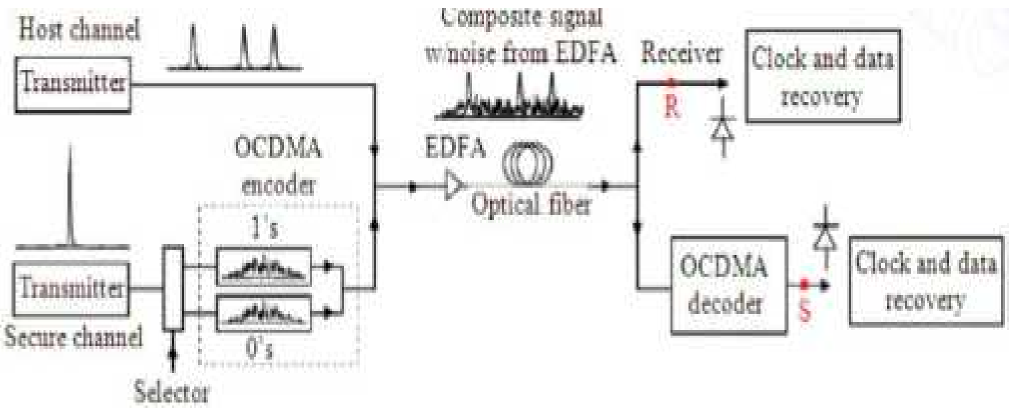


Figure Hybrid System

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

Solitons:

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

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

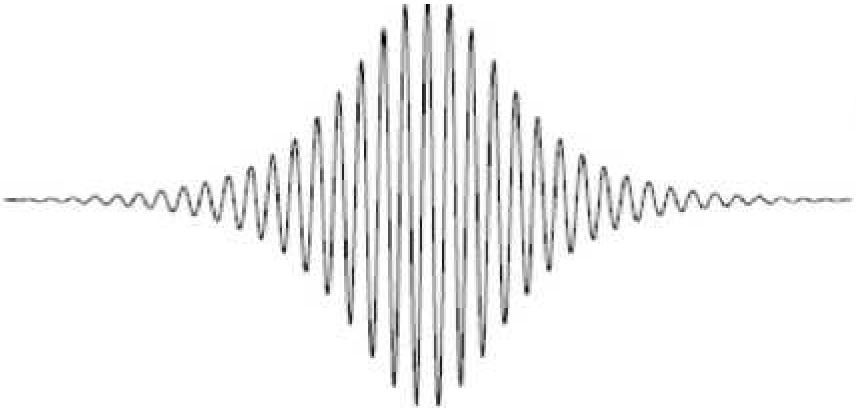


Figure soliton pulse -envelope

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

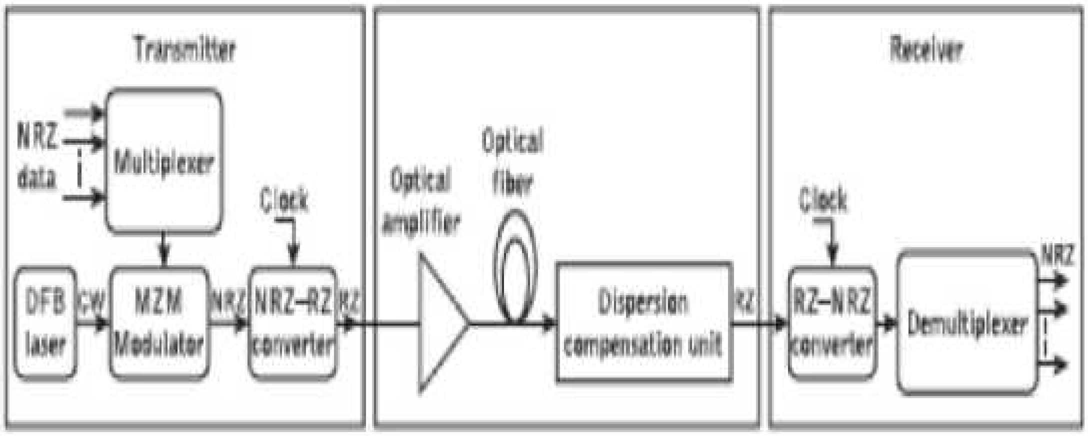


Figure Block schematic of optical fiber soliton transmission system

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

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

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

$$qo = T_o / 2\tau$$

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

Ultra High Capacity Networks

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

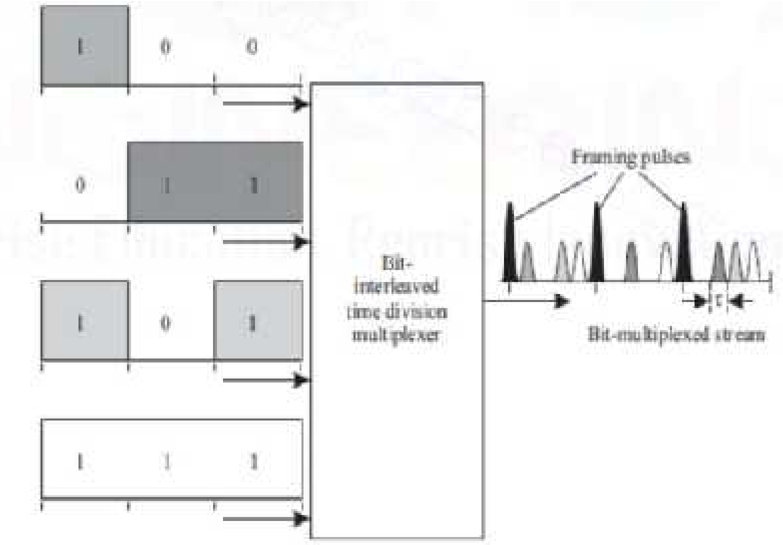


Figure Bit interleaved optical TDM

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

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

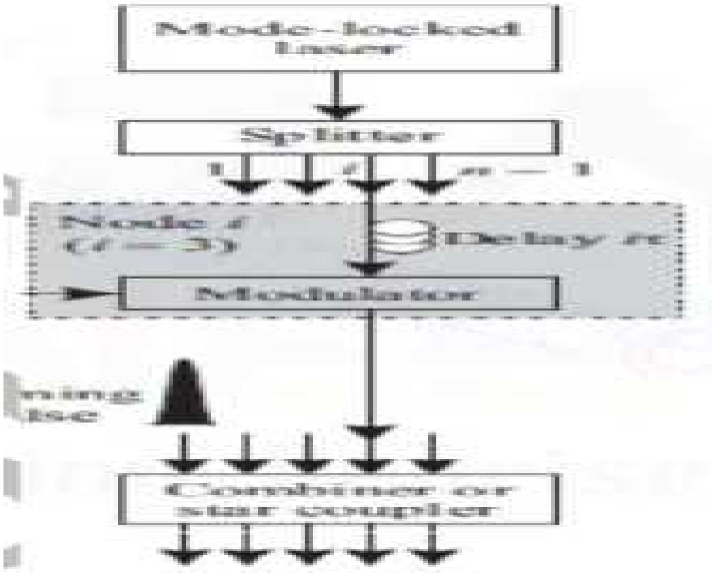


Figure optical multiplexer to create nit interleaved TDM Stream Since the velocity of light in silica fiber is about 2 × 108 m/s, 1 meter of fiber provides a delay of about 5 ns.

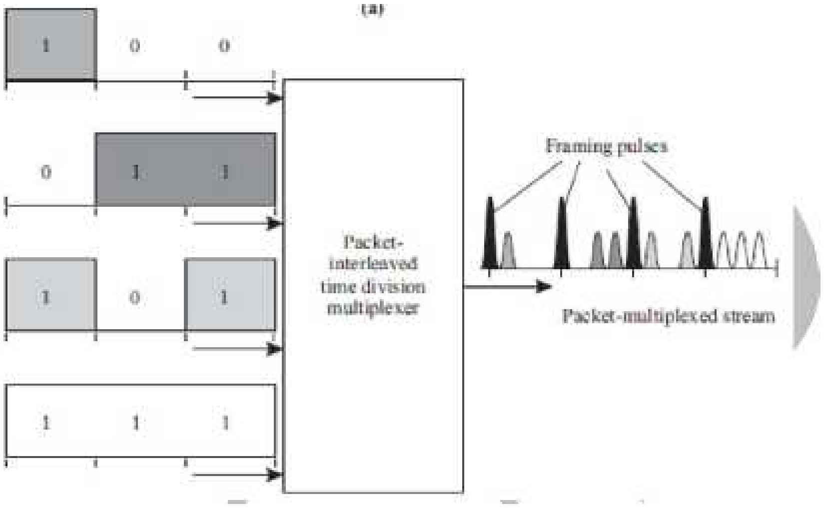
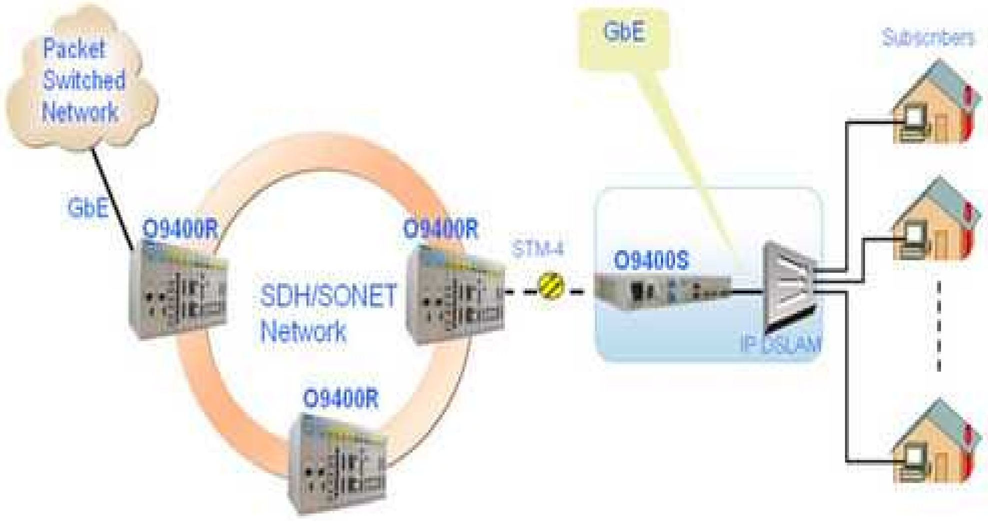


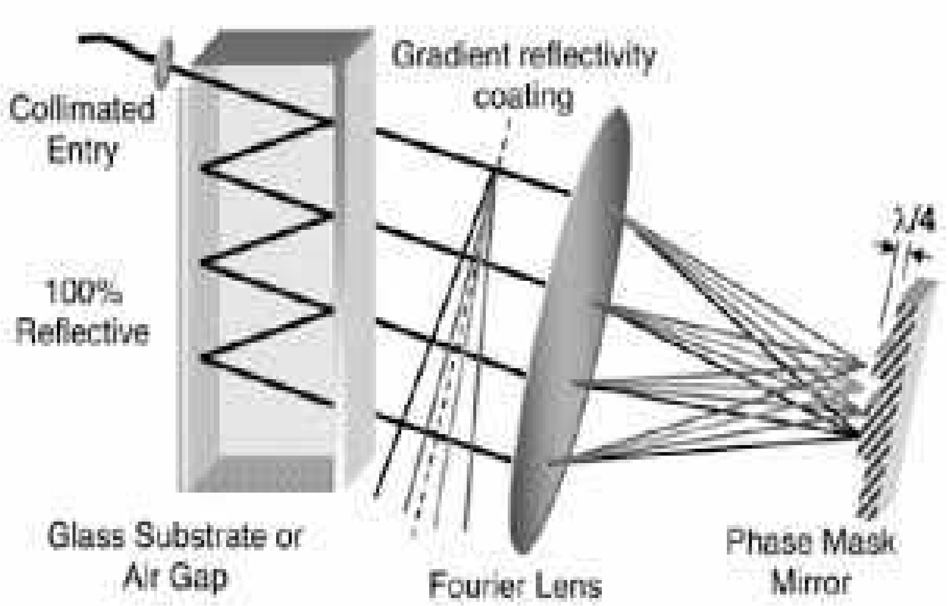
Figure packet interleaved optical TDM

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

APPLICATIONS



Examples of Remote Device Management & Optical SDH Application Distributor



Examples of Emerging Optical CDMA application

POST TEST-MCQ TYPE

1. Each stage of information transfer is required to follow the fundamentals of
a) Optical interconnection
b) Optical hibernation
c) Optical networking
d) Optical regeneration

2. What is a multi-functional element of optical network?
a) Hop
b) Optical node
c) Wavelength
d) Optical attenuation

3. A signal carried on a dedicated wavelength from source to destination node is known as a
a) Light path
b) Light wave
c) Light node
d) Light source

4. The fundamentals of optical networking are divided into _______ areas.
a) Two
b) One
c) Four
d) Three

5. The optical networking fundamentals are _____________ of the transmission techniques.
a) Dependent
b) Independent
c) Similar
d) Dissimilar

6. What are the array of switches which forms circuit switching fabrics?
a) Packet arrays
b) Optical cross connects
c) Circuit arrays
d) Optical networks

7. Which of the following is an example of a static circuit-switched network?
a) OXC
b) Circuit regenerator
c) Packet resolver
d) SDH/SONET

8. What is the main disadvantage of OCS?
a) Regenerating mechanism
b) Optical session
c) Time permit
d) Disability to handle burst traffic

9. Optical electro-conversions takes place in _________________ networks.
a) Sessional
b) Optical packet-switched
c) Optical circuit-switched
d) Circular

10. How many functions are performed by an optical packet switch?
a) Four
b) Three
c) Two
d) One

11. Which provides data storage for packets to resolve contention problems?
a) Switching
b) Routing
c) Buffering
d) Reversing

12. What is usually required by a packet to ensure that the data is not overwritten?
a) Header
b) Footer
c) Guard band
d) Payload

13. Which of the following provides efficient designation, routing, forwarding, switching of traffic through an optical packet-switched network?
a) Label correlation
b) Multiprotocol label switching
c) Optical correlation
d) Routing

14. Electrical devices in optical network are basically used for _____________
a) Signal degradation
b) Node transfer
c) Signal control
d) Amplification

15. A _____________ digital hierarchy was required to enable the international communications network to evolve in the optical fiber era.
a) Asynchronous
b) Dedicated
c) Seismic
d) Synchronous

16. Which is a packetized multiplexing and switching technique which combines the benefits of circuit and packet switching?
a) Synchronous mode
b) Asynchronous transfer mode
c) Circuit packet
d) Homogeneous mode

17. An advanced type of reconfigurable OTN is referred to as an ________________
a) Automatic OTN
b) Auto-generated photon
c) Automatically switched optical network
d) Optical reimbursement

18. The mapping of IP frames in SDH/SONET is accomplished in ____________ stages.
a) Four
b) Two
c) Three
d) One

19. Which supports a great number of wavelength channels and reduces the number of switches within the optical network?
a) Waveband switching
b) Optical remuneration
c) Optical genesis
d) Wavelength multiplexing

20. The routing and wavelength assignment problem addresses the core issue of
a) Traffic patterns in a network
b) Wavelength adjustment
c) Wavelength continuity constraint
d) Design problem

21. How many techniques of implementation are there for routing wavelength assignment (RWA)?
a) Two
b) Six
c) Three
d) Four

22. The ___________ provides information about the physical path and wavelength assignment for all active light paths.

a) Network state
b) RWA
c) LAN topology
d) Secluded communication protocol

23. Which is a network that connects several regional or national networks together?

a) Long-haul network
b) Domain network
c) Short-haul network
d) Erbium network

24. What is the range of transmission of extended long haul network?

a) 200-400 km
b) 600-1000 km
c) 1000-2000 km
d) 2000-4000 km

25. What is the range of transmission of ultra-long haul network?

a) 200-400 km
b) 600-1000 km
c) 1000-2000 km
d) 2000-4000 km

26. Which feature plays an important role in making the longer haul networks feasible?

a) Channeling
b) Forward error control
c) Backward error control
d) Interconnection

27. Which of the following is not an element of a submerged cable system?

a) Repeater
b) Branching unit
c) Gain equalizer
d) Attenuator

28. Which provides interconnection between the United States and European countries?

a) TAT
b) WTE
c) PFE
d) POP

29. A single fiber in TAT-14 can carry **_________** wavelength channels.
a) One
b) Twelve
c) Sixteen
d) Ten

30. Optical MAN’S are usually structured in **_______** topologies.
a) Ring
b) Bus
c) Mesh
d) Star

31. What is the exception in the similarities between the optical Ethernet and the Ethernet LAN?
a) Physical layer
b) Data-link layer
c) Refractive index
d) Attenuation mechanism

32. Which technology is used by optical Ethernet?
a) GP-technology
b) HJ-technology
c) IP-technology
d) GB-technology

33. Optical Ethernet can operate at the transmission rates as low as
a) 10 M bits per second
b) 40 M bits per second
c) 100 M bits per second
d) 1000 M bits per second

34. How many types of optical Ethernet connections are developed?
a) Two
b) One
c) Four
d) Three

35. Which type of connection can be used as an Ethernet switch?
a) Point-to-point
b) Multipoint-to-multipoint
c) Multipoint-to-point
d) Point-to-multipoint

36. The **_______________** provides point-to-point access to a bidirectional single-mode optical fiber.
a) Optical regenerator
b) Optical session
c) Optical distribution node
d) Optical buffer

37. The **___________** protocol is not used when the Ethernet connections are configured for a full duplex operation.
a) TCP/IP
b) MAC
c) CSMA/CD
d) DTH

38. Optical Ethernet provides switching capabilities in layers
a) 1 and 2
b) 2 and 3
c) 3 and 4
d) 1 and 4

39. The more advantages optical amplifier is
a) Fiber amplifier
b) Semiconductor amplifier
c) Repeaters
d) Mode hooping amplifier

40. Which of the following cannot be used for wideband amplification?
a) Semiconductor optical amplifier
b) Erbium-doped fiber amplifier
c) Raman fiber amplifier
d) Brillouin fiber amplifier

41. Which of the following is used preferably for channel selection in a WDM system?
a) Semiconductor optical amplifier
b) Erbium-doped fiber amplifier
c) Raman fiber amplifier
d) Brillouin fiber amplifier

42. For used in single-mode fiber **__________** are used preferably.
a) Semiconductor optical amplifier
b) Erbium-doped fiber amplifier
c) Raman fiber amplifier
d) Brillouin fiber amplifier

43. _______________ is superior as compared to _________________

a) TWA, FPA
b) FPA, TWA
c) EDFA, FPA
d) FPA, EDFA

44. Signal amplification is obtained in

a) Erbium-doped fluoro-zir-carbonate fiber multimode
b) Rare-earth-doped fiber amplifiers
c) Raman fiber systems
d) Brillouin fiber amplifier

45. Which is constructed using erbium-doped glass?

a) Erbium-based micro fiber amplifier
b) Rare-earth-doped fiber amplifiers
c) Raman fiber systems
d) Brillouin fiber amplifier

46. In _____________ Rayleigh scattering can be reduced.

a) An erbium-based micro fiber amplifier
b) Rare-earth-doped fiber amplifiers
c) Raman fiber systems
d) Distributed Raman amplification

47. Which is defined as a process by which the wavelength of the transmitted signal is changed without altering the data carried by the signal?

a) Wavelength conversion
b) Attenuation
c) Sigma management
d) Wavelength dispersion

48. The device which is used to perform wavelength conversion is called as

a) Attenuator
b) Wavelength Gyrator
c) Wavelength Circulator
d) Wavelength translator

49. The ___________ converters cannot process different modulation formats.

a) Shifting
b) Optoelectronic wavelength
c) Opt-circular
d) Magnetic simulating

50. Which of the following is NOT an application of optical amplifier?
a) Power amplifier
b) In-line repeater amplifier
c) Demodulator
d) Preamplifier

51. What is the typical range of the noise figure?
a) 1 – 2 dB
b) 3 – 5 dB
c) 7 – 11 dB
d) 12 – 14 dB

52. A major attribute of coherent optical transmission was its ability to provide ________________ for future multicarrier systems and networks.
a) Attenuation
b) Dispersion
c) Frequency selectivity
d) Noisy carriers

53. A multicarrier modulation format in which there has been growing interest to compensate for impairments in optical fiber transmission systems is
a) OFDM
b) EDM
c) WDM
d) ADM

54. WDM stands for?
a) Wave division multiplexing
b) Wavelength division multiplexing
c) Wavelength dependent multiplexing
d) Wave dependent multiplexing

55. A technique that can be a solution to the problem of synchronizing data sources.
a) framing
b) data link control
c) full link control
d) pulse stuffing

56. Wavelength Division Multiplexing (WDM) is an analog multiplexing technique to combine
a) magnetic signals
b) electromagnetic signals
c) digital signals
d) optical signals

57. EDFAs generally operate in the wavelength region near

a) 1550 nm and can offer capacities exceeding 1000 Gbps.
b) 850 nm and can offer capacities around 100 Gbps.
c) 1150 nm and can offer capacities around 1000 Gbps.
d) 1550 nm and can offer capacities around 100 Gbps.

58. Which wavelength is the most appropriate one for pumping an EDFA?

a) 850 nm
b) 980 nm
c) 1300 nm
d) 1550 nm

59. The main difference between an SOA and an EDFA is that

a) An SOA operates in the electrical domain, whereas the EDFA operates in the optical domain.
b) An SOA is pumped electrically, whereas the EDFA is pumped optically.
c) An SOA is pumped optically, whereas the EDFA is pumped electrically.
d) An SOA amplifies 1300 nm wavelength, whereas the EDFA amplifies 1550 nm.

60. Which band specifies the operation of EDFA?

a) O band
b) X band
c) C band
d) S band

61. Basically, Solitons are pulses which propagate through the fiber without showing any variation in

a) Amplitude
b) Shape
c) Velocity
d) All of the above

62. DWDM stands for

a) Digital Wavelength-Division Modulation
b) Dense Wavelength-Division Modulation
c) Double Wavelength-Division Modulation
d) Dense Wavelength-Division Multiplexing

63. In SONET, OC-1 stands for

a) Optical Carrier level one
b) Optical Coupler unidirectional
c) Optical Channel one
d) Optical Cable type 1

CONCLUSION

In this unit, Basic Networks of SONET / SDH, Broadcast and select WDM Networks, Wavelength Routed Networks, Power budget, Noise Effects on System Performance, EDFA system, Solitons, Optical CDMA, Ultra High Capacity Networks were discussed in detailed.

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ASSIGNMENT

1. Discuss the concepts of Media Access Control protocols in Broadcast and select networks.
2. Explain the basics of optical CDMA systems.
3. Explain the features of Ultra High Capacity networks
4. Explain the principle of WDM networks.
5. Discuss the nonlinear effects on optical network performance.
6. With suitable example explain the conditions and constraints in the formulation and solution of routing and wavelength assignment in an optimal way
7. Write a note on Solitons
8. Explain in detail different types of broadcast and select WDM networks
9. Explain SONET layers and frame structure with diagram. What is a four fiber BLSR ring in a SONET?