SKP Engineering College

Tiruvannamalai – 606611

A Course Material

on

Optical Communication and Networks

By

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Quality Certificate

This is to Certify that the Electronic Study Material

Subject Code: EC6702

Subject Name Optical Communication and Networks

Year/Sem:IV/VII

Being prepared by me and it meets the knowledge requirement of the University curriculum.

Signature of the Author

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This is to certify that the course material being prepared by Mr. M.Mageshbabu is of the adequate quality. He has referred more than five books and one among them is from abroad author.

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Signature of the Principal

Name: Dr.V.Subramania Bharathi

Seal:

EC6702 OPTICAL COMMUNICATION AND NETWORKS L T P C 3 0 0 3

UNIT I INTRODUCTION TO OPTICAL FIBERS 9

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 conceptsLinearly Polarized Modes -Single Mode Fibers-Graded Index fiber structure.

UNIT II SIGNAL DEGRADATION OPTICAL FIBERS 9

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

UNIT III FIBER OPTICAL SOURCES AND COUPLING 9

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

UNIT IV FIBER OPTIC RECEIVER AND MEASUREMENTS 9

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

UNIT V OPTICAL NETWORKS AND SYSTEM TRANSMISSION 9

Basic Networks – SONET / SDH – Broadcast – and –select WDM Networks – Wavelength Routed Networks – Non linear effects on Network performance –-Link Power budget -Rise time budgetNoise Effects on System Performance-Operational

Principles of WDM Performance of WDM + EDFA system – Solutions – Optical CDMA – Ultra High Capacity Networks.

TOTAL: 45 PERIODS

OUTCOMES:

Upon completion of the course, students will be able to:

- Discuss the various optical fiber modes, configurations and various signal degradation factors associated with optical fiber.
- Explain the various optical sources and optical detectors and their use in the optical communication system.
- Analyze the digital transmission and its associated parameters on system performance.

TEXT BOOKS:

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

REFERENCES:

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

CONTENTS

Unit I

Introduction Of Optical Fiber

Part-A

1. Write the expression for the refractive index in graded index fibers [CO1-L1]

$n(r)= n1[1-2\Delta(r/a)^{\alpha}]^{1/2}$ for 0<=r<=a

$n1(1-2\Delta)^{1/2}$ ~ n1(1-∆) =n2 for r>=a r

radial distance from fiber axis

a-core radius

n1-refractive index at the core

n2-refractive index at the cladding

α-shape of the index profile

∆ - index difference

2. Define Mode-field diameter [CO1-L1]

The fundamental parameter of a single mode fiber is the mode-field diameter. This can be determined from the mode field distribution of the fundamental LPo1 mode.

3. Give the expression for linearly polarized waves. [CO1-L1]

The electric or magnetic field of a train of plane polarized waves travelling in a direction k can be represented in the general form

$A(x,t) = e_i Aoexp[j(wt-k.x)]$With

$x=xe_x+ye_y+ze_z$ representing a general position vector and

$k=k_xe_x+k_ye_y+k_ze_z$ representing the wave propagation vector.

4. What is Snell's law? [CO1-L1]

The relationship at the interface is known as Snell's law and is given by

$n_1 \sin\Phi_1=n_2 \sin\Phi_2$

5. What is the necessity of cladding for an optical fiber? [CO1-L1]

a) To provide proper light guidance inside the core

b) To avoid leakage of light from thAe fiber

c) To avoid mechanical strength for the fiber

d) To protect the core from scratches and other mechanical damages

6. What are the uses of optical fibers? [CO1-L1]

(a) To transmit the information which are in the form of coded signals of the telephone communication, computer data, etc.

(b) To transmit the optical images

(c) To act as a light source at the inaccessible places.

(d) To act as sensors to do mechanical, electrical and magnetic measurements.

7. What is the principle used in the working of fibers as light guides? [CO1-L1]
The phenomenon of total internal reflection is used to guide the light in the optical fiber. To get total internal reflection, the ray should travel from denser to rarer i.e. from core to clad region of the fiber and the angle of incidence in the denser medium should be greater than the critical angle of that medium.

8. What are step index and graded index fibers? [CO1-L1]
In the case of graded index fiber, the refractive index of a core is a constant and is larger than the refractive index of the cladding. The light propagation is mainly by meridional rays. In the case of graded index fiber (GRIN fiber) the refractive index of the core varies parabolically from the center of the core having maximum refractive index to the core-cladding interface having constant minimum refractive index. Here the light propagation is by skew rays.

9. Why do we prefer step index single mode fiber for long distance communication? [CO1-L1]
Step index single mode fiber has
a) Low attenuation due to smaller core diameter
b) Higher bandwidth and
c) Very low dispersion.

10. What are meridional rays? [CO1-L1]
Meridional rays are the rays following Zig Zag path when they travel through fiber and for every reflection it will cross the fiber axis.

11. What are skew rays? [CO1-L1]
Skew rays are the rays following the helical path around the fiber axis when they travel through the fiber and they would not cross the fiber axis at any time.

12. What are the conditions for total internal reflection? [CO1-L1]
a) Light should travel from denser medium to rarer medium.
b) The angle of incidence should be greater than the critical angle of the denser medium.

13. Give the relation between numerical aperture of skew rays and meridional rays. [CO1-L1]
$(N.A)_{skew} = \cos\gamma (N.A)_{meridional}$ when the fiber is placed in air.
Here γ is the half of the angular change in every reflection.

14. When do you have phase shift during total internal reflection of light? [CO1-L1]
When the light ray travels from denser medium to rarer medium, if the angle of incidence is greater than the critical angle of core medium, there is a phase shift for both TE and TM waves

15. What is fiber birefringence? [CO1-L1]
Imperfections in the fiber are common such as asymmetrical lateral stress, non-circular imperfect variations of refractive index profile. These imperfections break the circular symmetry of ideal fiber and mode propagate with different phase velocity and the difference between their refractive index is called fiber birefringence.

$$B=k_o(n_y-n_x)$$

16. Give the expression for the numerical aperture in graded index fibers. [CO1-L1]

$N.A(r)=N.A.(0)\ (1-(r/a)^{\alpha})^{1/2}$ for $r<=a$

where N.A(0) = axial numerical aperture = $(n_1^2-n_2^2)1/2$ a is core radius and α is the refractive index profile.

17. Define acceptance angle. [CO1-L1]
The maximum angle 'Φmax'with which a ray of light can enter through the entrance end of the fiber and still be totally internally reflected is called acceptance angle of the fiber

18. What is internal reflection? [CO1-L1]
When the reflection of light is of a less optically dense material, it is called internal reflection.

19. What is external reflection? [CO1-L1]
When light travelling in a certain medium is reflected off an optically denser material it is referred to as external reflection

Part-B

1. Explain in detail about element of optical fiber communication system. [CO1-L2]

An optical fiber communication system is similar in basic concept to any type of communication system. A block schematic of a general communication system is shown in Figure 1.2(a), the function of which is to convey the signal from the information source over the transmission medium to the destination. The communication system therefore consists of a transmitter or modulator linked to the information source, the transmission medium, and a receiver or demodulator at the destination point. In electrical communications the information source provides an electrical signal, usually derived from a message signal which is not electrical (e.g. sound), to a transmitter comprising electrical and electronic components which converts the signal into a suitable form for propagation over the transmission medium. This is often achieved by modulating a carrier, which, as mentioned pre- viously, may be an electromagnetic wave.

For optical fiber communications the system shown in Figure 1.1(a) may be considered in slightly greater detail, as given in Figure 1.1(b). In this case the information source pro- vides an electrical signal to a transmitter comprising an electrical stage which drives an optical source to give modulation of the light wave carrier. The optical source which pro- vides the electrical–optical conversion may be either a semiconductor laser or light-emitting diode (LED).

The transmission medium consists of an optical fiber cable and the receiver consists of an optical detector which drives a further electrical stage and hence provides demodulation of the optical carrier. Photodiodes (*p–n*, *p–i–n* or avalanche) and, in some instances, phototransistors and photoconductors are utilized for the detection of the optical signal and the optical–electrical conversion. Thus there is a requirement for electrical interfacing at either end of the optical link and at present the signal processing is usually performed electrically.

The optical carrier may be modulated using either an analog or digital information signal. In the system shown in Figure 1.1(b) analog modulation involves the variation of the light emitted from the optical source in a continuous manner. With digital modulation, however, discrete changes in the light intensity are obtained (i.e. on–off pulses). Although often simpler to implement, analog modulation with an optical fiber communication sys- tem is less efficient, requiring a far higher signal-to-noise ratio at the receiver than digital modulation. Also, the linearity needed for analog modulation is not always provided by semiconductor optical sources, especially at high modulation frequencies. For these reasons, analog optical fiber communication links are generally limited to shorter distances and lower bandwidth operation than digital links.

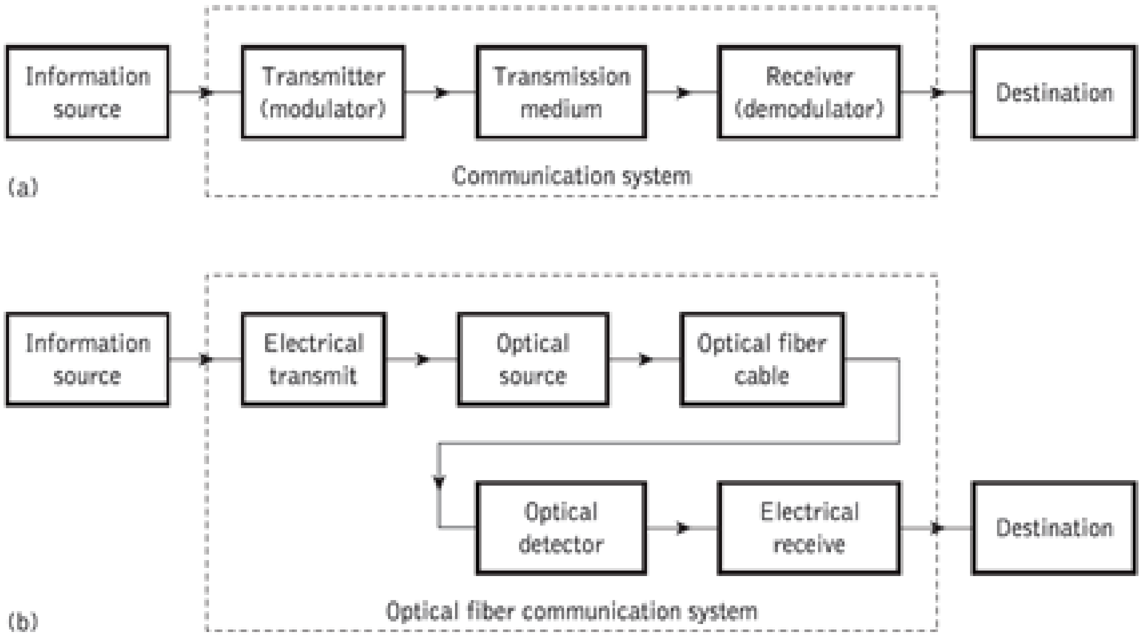


Figure 1.1 (a) The general communication system. (b) The optical fiber communication system

2. Describe the total internal reflection. [CO1-L2]

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. The refractive index of amedium is defined as the ratio of the velocity of light in a vacuum to the velocity of light in the medium.

A ray of light travels more slowly in an optically dense medium than in one that is less dense, and the refractive index gives a measure of this effect. When a ray is incident on the interface between two dielectrics of differing refractive indices (e.g. glass–air), refraction occurs, as illustrated in Figure 1.2(a). It may be observed that the ray approaching the interface is propagating in a dielectric of refractive index n_1 and is at an angle φ_1 to the normal at the surface of the interface. If the dielectric on the other side of the interface has a refractive index n_2 which is less than n_1, then the refraction is such that the ray path in this lower index medium is at an angle φ_2 to the normal, where φ_2 is greater than φ_1. The angles of incidence φ_1 and refraction φ_2 are related to each other and to the refractive indices of the dielectrics by Snell's law of refraction, which states that:

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

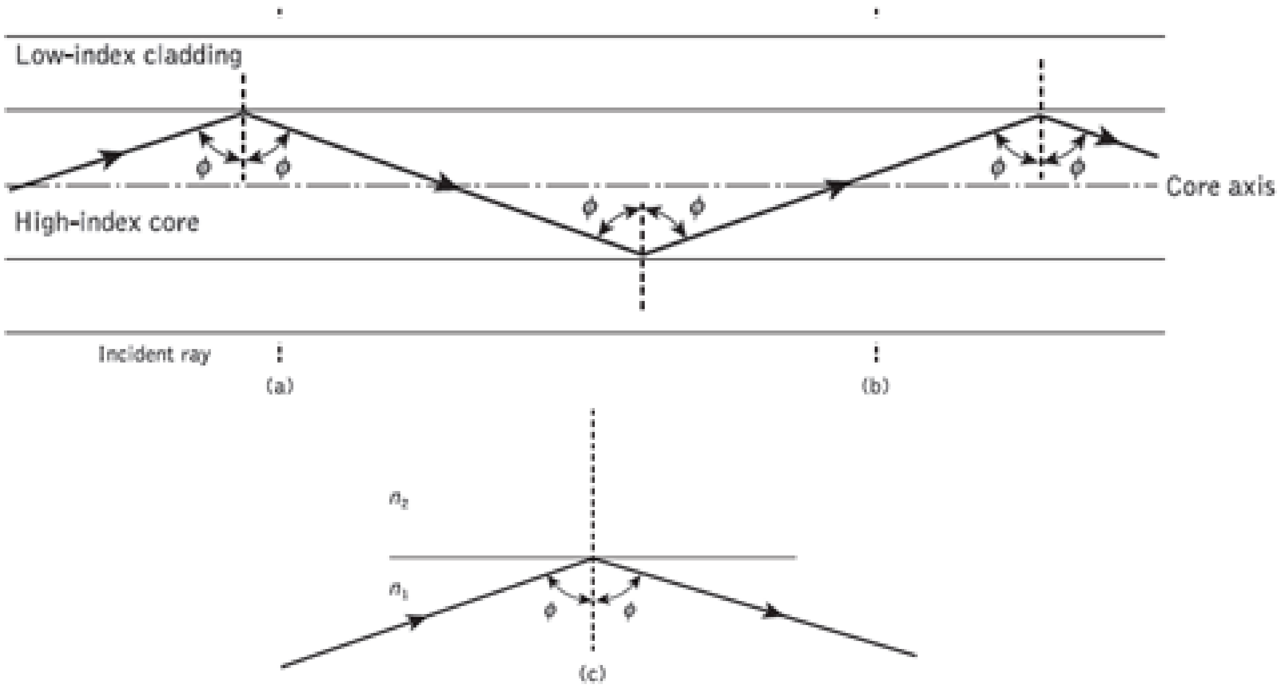


Figure 1.2 Light rays incident on a high to low refractive index interface (e.g. glass air): (a) refraction; (b) the limiting case of refraction showing the critical ray at an angle φ_c (c) total internal reflection where $\varphi > \varphi_c$

It may also be observed in Figure 1.2(a) that a small amount of light is reflected back into the originating dielectric medium (partial internal reflection). As n_1 is greater than n_2, 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 incidencemust be less than 90°. 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 1.2(b). From Eq. (1.1) 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 1.2(c) 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° - φ_c) may be considered to propagate down an optical fiber with low loss.

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

Figure 1.3 illustrates the transmission of a light ray in an optical fiber via a series of total internal reflections at the interface of the silica core and the slightly lower refractive index silica cladding. The ray 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 1.3 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 1.3 assumes a perfect fiber, and that any discontinuities or imperfections at the core–cladding interface would probably result in refraction rather than total internal reflection, with the subsequent loss of the light ray into the cladding.

3. Derive an expression for numerical aperture of a step index fiber[CO1-H2]

The acceptance angle for an optical fiber was defined in the preceding section. However, it is possible to continue the ray theory analysis to obtain a relationship between the acceptance angle and the refractive indices of the three media involved, namely the core, cladding and air. This leads to the definition of a more generally used term, the numerical aperture of the fiber. It must be noted that within this analysis, as with the preceding discussion of acceptance angle, we are concerned with meridional rays within the fiber. Figure 1.5 shows a light ray incident on the fiber core at an angle θ_1 to the fiber axis which is less than the acceptance angle for the fiber θ_a. The ray enters the fiber from a medium (air) of refractive index n_0, and the fiber core has a refractive index n_1, which is slightly greater than the cladding refractive index n_2.

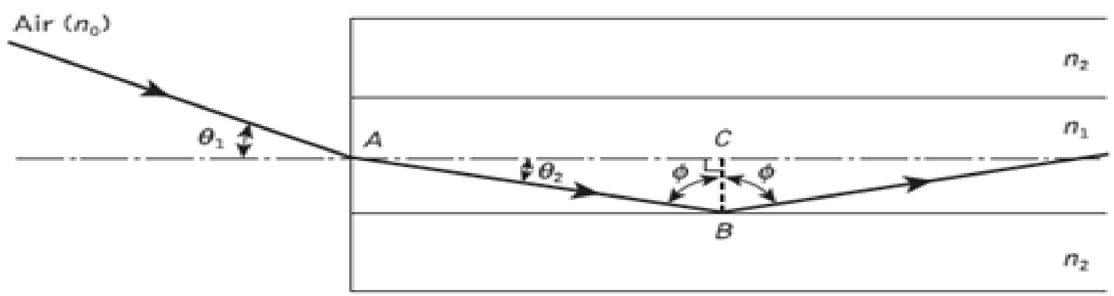


Figure 2.5 The ray path for a meridional ray launched into an optical fiber in air at an input angle less than the acceptance angle for the fiber

Assuming the entrance face at the fiber core to be normal to the axis, then considering the refraction at the air–core interface and using Snell's law given by Eq. (1.1)

$$n_0 \sin \theta_1 = n_1 \sin \theta_2 \tag{1.3}$$

Considering the right-angled triangle *ABC* indicated in Figure 2.5, then:

$$\phi = \frac{\pi}{2} - \theta_2 \tag{1.4}$$

where φ is greater than the critical angle at the core–cladding interface. Hence Eq. (1.3) becomes:

$$n_0 \sin \theta_1 = n_1 \cos \phi \tag{1.5}$$

Using the trigonometrical relationship $\sin^2 \phi + \cos^2 \phi = 1$, Eq. (1.5) may be written in the form:

$$n_0 \sin \theta_1 = n_1 (1 - \sin^2 \phi)^{\frac{1}{2}} \tag{1.6}$$

When the limiting case for total internal reflection is considered, φ becomes equal to the critical angle for the core–cladding interface and is given by Eq. (1.2). Also in this limiting case θ_1 becomes the acceptance angle for the fiber θ_a. Combining these limiting cases into Eq. (1.6) gives:

$$n_0 \sin \theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}} \tag{1.7}$$

Equation (1.7), apart from relating the acceptance angle to the refractive indices, serves as the basis for the definition of the important optical fiber parameter, the numerical aperture (*NA*). Hence the *NA* is defined as:

$$NA = n_0 \sin \theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}} \tag{1.8}$$

Since the *NA* is often used with the fiber in air where n_0 is unity, it is simply equal to sin θ_a. It may also be noted that incident meridional rays over the range $0 \le \theta_1 \le \theta_a$ will be propagated within the fiber. The *NA* may also be given in terms of the relative refractive index difference Δ between the core and the cladding which is defined as:

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \simeq \frac{n_1 - n_2}{n_1} \quad \text{for } \Delta \ll 1 \tag{1.9}$$

Hence combining Eq. (1.8) with Eq. (1.9) we can write:

$$NA = n_1(2\Delta)^{\frac{1}{2}} \quad (1.10)$$

The relationships given in Eqs (1.8) and (1.10) for the numerical aperture is a very useful measure of the light-collecting ability of a fiber. They are independent of the fiber core diameter and will hold for diameters as small as 8 μm. However, for smaller diameters they break down as the geometric optics approach is invalid. This is because the ray theory model is only a partial description of the character of light. It describes the direction a plane wave component takes in the fiber but does not take into account interference between such components. When interference phenomena are considered it is found that only rays with certain discrete characteristics propagate in the fiber core. Thus the fiber will only support a discrete number of guided modes. This becomes critical in small- core-diameter fibers which only support one or a few modes. Hence electromagnetic mode theory must be applied in these cases.

4. Distinguish step-index from graded index fibers. [CO1-L2]

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 1.14, which illustrates the two major types of step index fiber.

The refractive index profile may be defined as:
n(r)={n1 r<a core,n2 r>a cladding in both glass

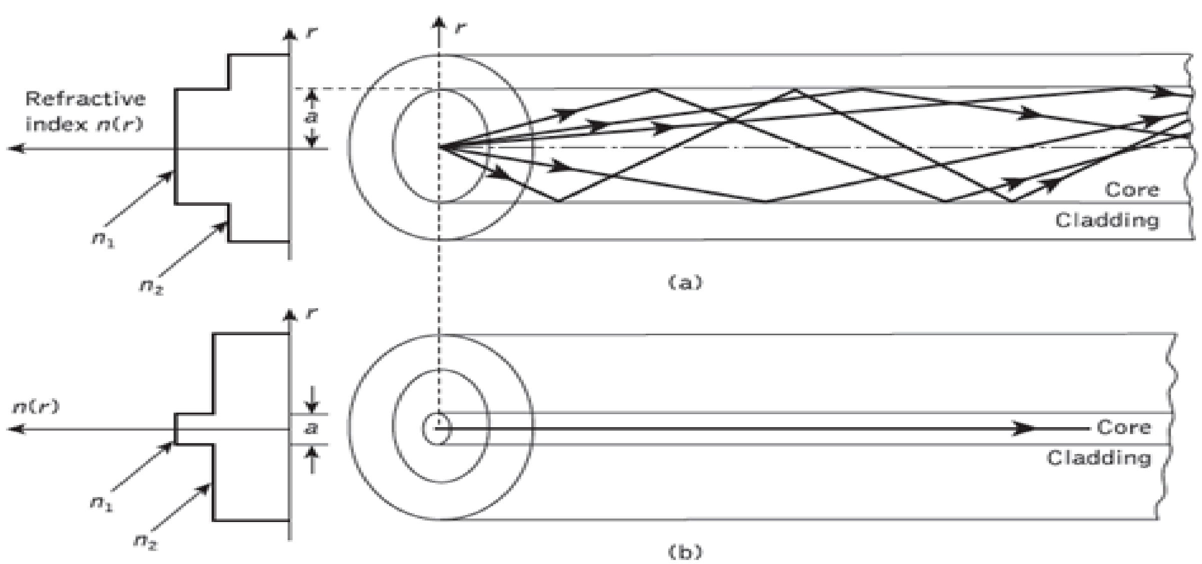


Figure 1.14 The refractive index profile and ray transmission in step index fibers: (a) multimode step index fiber; (b) single-mode step index fiber

Figure 1.14(a) shows a multimode step index fiber with a core diameter of around 50μm or greater, which is large enough to allow the propagation of many modes within the fiber core. This is illustrated in Figure 1.14(a) by the many different possible ray paths through the fiber. Figure 1.14(b) shows a single-mode or monomode step index fiber which allows the propagation of only one transverse electromagnetic mode (typically HE_{11}), and hence the core diameter must be of the order of 2 to 10μm. The propagation of a single mode is illustrated in Figure 1.14(b) as corresponding tosingle 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. 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 para- meters (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. that 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:

$$M_s \simeq \frac{V^2}{2}$$

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

Graded 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 1.14, which illustrates the two major types of step index fiber.

The refractive index profile may be defined as

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

where Δ 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 $\alpha = \infty$, a parabolic profile when $\alpha = 2$ and a triangular profile when $\alpha = 1$. This range of refractive index profiles is illustrated in Figure 1.15

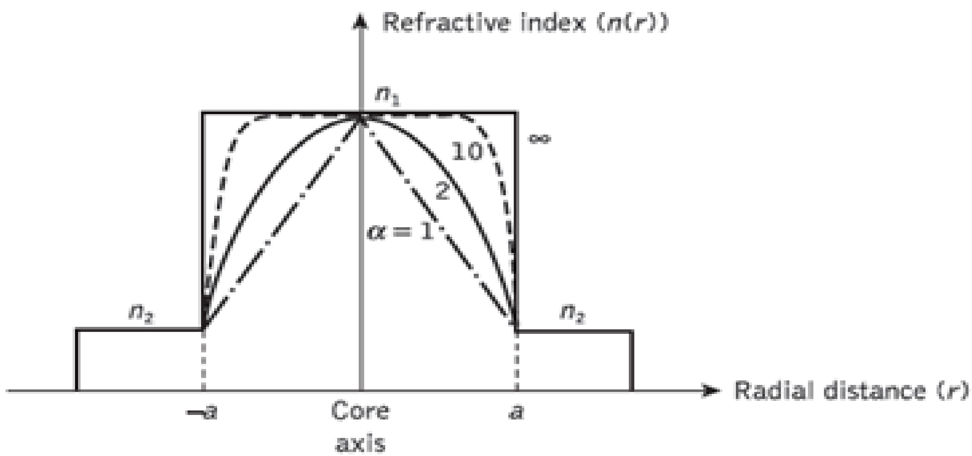


Figure 1.15 Possible fiber refractive index

The graded index profiles which at present produce the best results for multimode optical propagation have a near parabolic refractive index profile core with α⊐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.

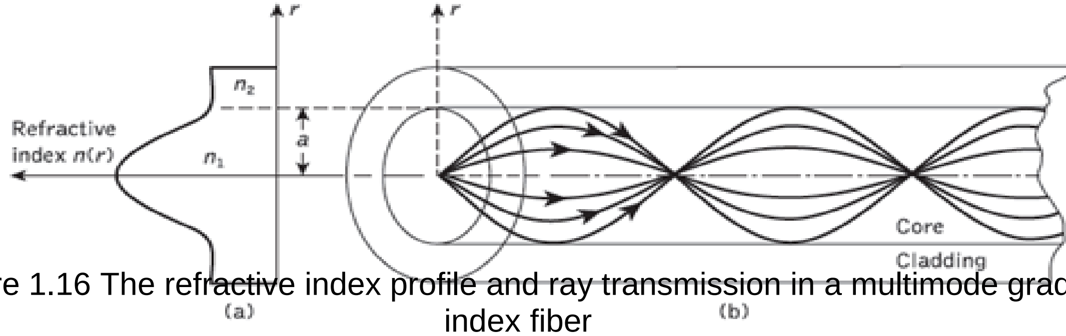


Figure 1.16 The refractive index profile and ray transmission in a multimode graded index fiber

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

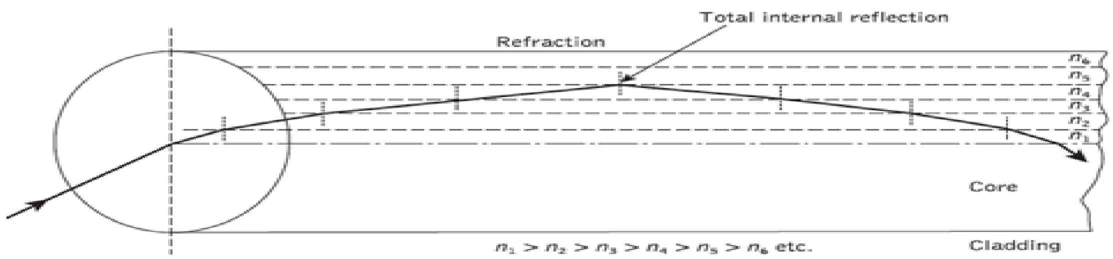


Figure 1.17 An expanded ray diagram showing refraction at the various high to low index interfaces within a graded index fiber, giving an overall curved ray path into the outer regions of the core.

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

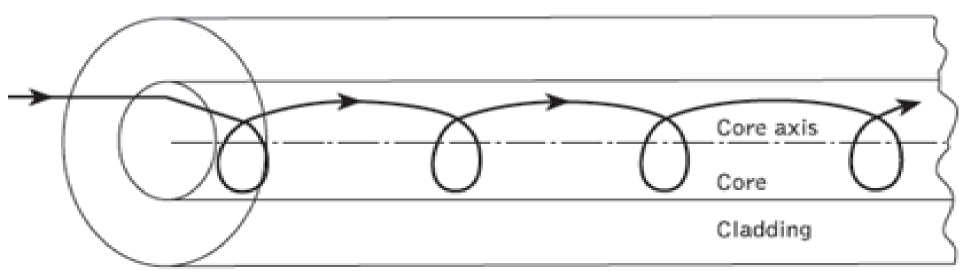


Figure 1.18 A helical skew ray path within a graded index fiber

However, the near axial rays are transmitted through a region of higher refractive index 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 illus- trated in Figure 1.18. These travel for the most part in the lower index region at greater speeds, thus giving the same mechanism of mode transit time equalization. Hence, multi- mode graded index fibers with parabolic or near-parabolic index profile cores have trans- mission bandwidths which may be orders of magnitude greater than multimode step index fiber bandwidths. Consequently, although they are not capable of the bandwidths attain- able with single-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.

Unit-II

Signal Degradation Of Optical Fiber

Part-A

1. What is Intra Modal Dispersion? [CO2-L1]

Intra Modal dispersion is pulse spreading that occurs within a single mode. The spreading arises from finite spectral emission width of an optical source. This phenomenon is also called as group velocity dispersion.

2. What are the causes of intra modal dispersion? [CO2-L1]

There is two main causes of intra modal dispersion. They are:

1. Material dispersion
2. Wave guide dispersion

3. What is material dispersion? [CO2-L1]

Material dispersion arises from the variation of the refractive index of the core material as a function of wavelength. Material dispersion is also referred to as chromatic dispersion. This causes a wavelength dependence of group velocity of given mode. So it occurs because the index of refraction varies as a function of optical wavelength. Material dispersion is an intra modal dispersion effect and is for particular importance for single ode wave-guide.

4. What is waveguide dispersion? [CO2-L1]

Wave guide dispersion which occurs because of a single mode fiber confines only about 80% of optical power to the core. Dispersion this arises since 20% of light propagates in cladding travels faster than the light confined to the core. Amount of wave-guide dispersion depends on fiber design. Other factor for pulse spreading is inter modal delay

5. What is group velocity? [CO2-L1]

If L is the distance traveled by the pulse, β is the propagation constant along axis then the group velocity in the velocity at which energy is a pulse travels along the fiber.

$$V_g = C. (d\beta / dk)$$

6. What is group delay? [CO2-L1]

In an optical fiber there are various modes present. Then the optical input, which is propagated along the fiber, will travel in various modes. Because of these modes the velocity of the signal will vary also there may be a delay in the optical signal of these various modes. This is called as the ‘Group Delay’.

7. What is polarization? [CO2-L1]

It is a fundamental property of an optical signal .It refers to the electric field orientation of a light signal which can vary significantly along the length of a fiber.

8. What is polarization Mode Dispersion? [CO2-L1]
The difference in propagation times between the two orthogonal polarization modes will result in pulse spreading. This is called as polarization Mode Dispersion.

9. What is pulse Broadening? [CO2-L1]
Dispersion induced signal distortion is that a light pulse will broaden as it travels along the fiber. This pulse broadening causes a pulse to overlap with neighboring pulses. After a time‘t’the adjacent pulses can no longer be individually distinguished at the receiver and error will occur.

10. What is Mode Coupling? [CO2-L1]
It is another type of pulse distortion which is common in optical links. The pulse distortion will increase less rapidly after a certain initial length of fiber due to this mode coupling and differential mode losses. In initial length coupling of energy from one mode to another arises because of structural irregularities, fiber dia. etc.

11. What is Profile Dispersion? [CO2-L1]
A fiber with a given index profile (alpha) will exhibit different pulse spreading according to the source wavelength used. This is called as Profile Dispersion.

12. What is Matched Cladding fiber? [CO2-L1]
Fibers that have a uniform refractive index throughout the cladding is called Matched cladding fiber.

13. What is Depressed cladding fiber? [CO2-L1]
In depressed cladding fiber the cladding portion next to the core has a lower index than the outer cladding region.

14. Define depresion shifted fiber. [CO2-L1]
By creating a fiber with large negative waveguide dispersion & assuming the same values for material dispersion as in a standard single mode fiber the addition of waveguide & material dispersion can then shifted to zero dispersion point to long wavelength. The resulting optical fiber are known as dispersion shifted fiber.

15. Define dispersion flattening? [CO2-L1]
The reduction of fiber dispersion by spreading the dispersion minimum out overa wide range this approach is known as dispersion flattering.

16. What is effective cut-off wavelength? [CO2-L1]
It is defined as the largest wavelength at which the higher order LP11 mode power relative to the fundamental LP01 mode power is reduced to 0.1db.

17. What is intramodal dispersion? [CO2-L1]

The intramodal dispersion depends on wavelength and its effect on signal distortion increases with the spectral width of the optical source. (It is a band of wavelength over which the source emits light.

18. Write a note on scattering losses. [CO2-L1]

Scattering losses in glass arise from microscopic variation in the material density from compositional fluctuation and from structural in homogeneities or defects occurring during fiber manufacture.

19. What is Rayleigh scattering? [CO2-L1]

The index variation causes a Rayleigh type of scattering of light. Rayleigh scattering in glass in the same phenomenon that scatters light from sun in the atmosphere, giving rise to blue sky. The expression for Rayleigh scattering loss is given by

$\alpha_{scat}=(8\pi^3/3\lambda^2)(n^21)^2 k_B T_f \beta_T$

n = refractive index

k_B = boltzman constant

β_T= isothermal compressibility

T_f =fictive temperature,

λ =operativewavelength

20. What is intermodal dispersion?[CO2-L1]

Intermodal dispersion is a pulse spreading that occurs within a single mode. The spreading arises from finite spectral emission width of an optical source. it is called group velocity dispersion or intermodal dispersion

21. What is intramodal delay? [CO2-L1]

The other factor giving rise to pulse spreading is intramodal delay which is a result of each mode having a different value of Group velocity at a single frequency.

Part-B

1. Distinguish intrinsic absorption and extrinsic absorption[CO2-L2]

Intrinsic absorption

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

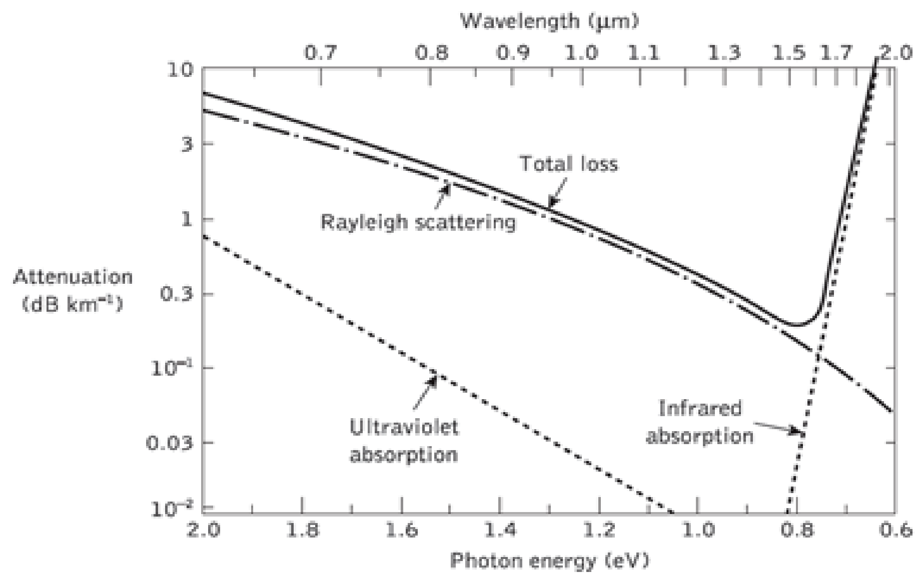


Figure 2.1 The attenuation spectra for the intrinsic loss mechanisms in pure GeO_2–SiO_2 glass

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

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

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

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

Extrinsic absorption

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

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

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

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

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

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

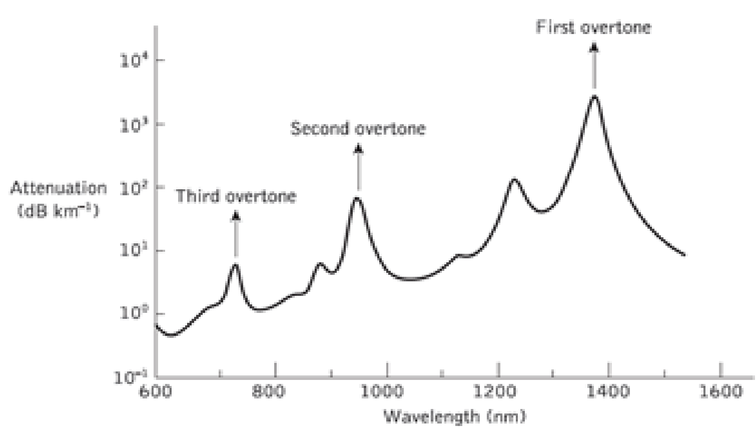


Figure 2.2 The absorption spectrum for the hydroxyl (OH) group in silica.

Furthermore, combinations between the overtones and the fundamental SiO_2 vibration occur at 1.24, 1.13 and 0.88 μm, completing the absorption spectrum shown in Figure 2.2.It may also be observed in Figure 3.2 that the only significant absorption band in the region below a wavelength of 1 μm is the second overtone at 0.95 μm which causes attenuation of about 1 dB km^{-1} for one part per million (ppm) of hydroxyl.

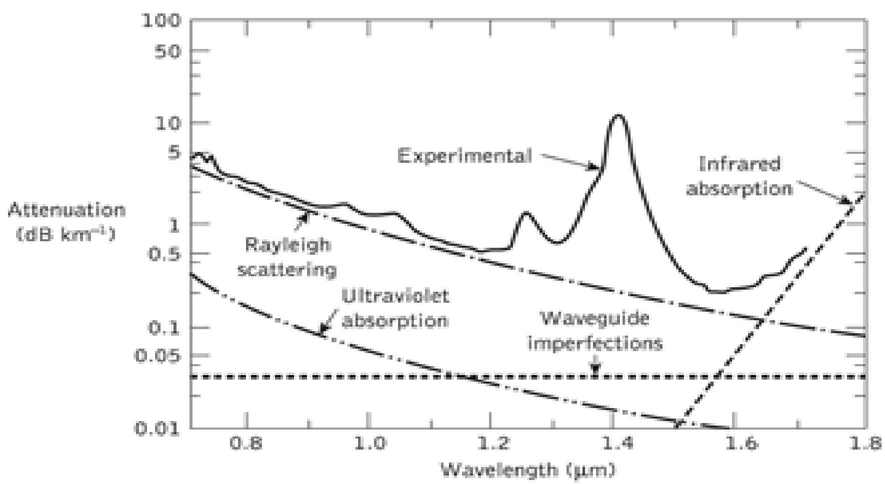


Figure 2.3 The measured attenuation spectrum for an ultra-low-loss single-mode fiber (solid line) with the calculated attenuation spectra for some of the loss mechanisms contributing to the overall fiber attenuation

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

Although in standard, modern single-mode fibers the loss caused by the primary OH peak at 1.383 μm has been reduced below 1 dB km^{-1}, it still limits operation over significant distances to the lower loss windows at 1.31 and 1.55 μm.

2. Explain linear scattering losses. [CO2-L1]

Linear scattering mechanisms cause the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly (proportionally to the mode power) into a different mode. This process tends to result in attenuation of the transmitted light as the transfer may be to a leaky or radiation mode which does not continue to propagate within the fiber core, but is radiated from the fiber. It must be noted that as with all linear processes, there is no change of frequency on scattering. Linear scattering may be categorized into two major types: Rayleigh and Mie scattering. Both result from the non ideal physical properties of the manufactured fiber which are difficult and, in certain cases, impossible to eradicate at present.

3. Distinguish Rayleigh scattering and Mie scattering. [CO2-L2]

Rayleigh scattering

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

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

The subsequent scattering due to the density fluctuations, which is in almost all directions, produces attenuation proportional to 1/λ4 following the Rayleigh scattering formula. For a single-component glass this is given by:

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F$$

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

$$\mathscr{L} = \exp(-\gamma_R L)$$

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

Mie scattering

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

The scattering created by such inhomogeneities is mainly in the forward direction and is called Mie scattering. Depending upon the fiber material, design and manufacture, Mie scattering can cause significant losses. The inhomogeneities may be reduced by: removing imperfections due to the glass manufacturing process; carefully controlled extrusion and coating of the fiber,increasing the fiber guidance by increasing the relative refractive index difference

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

5. Explain in detail about fiber bend loss. [CO2-L1]

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

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

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

where *R* is the radius of curvature of the fiber bend and c_1, c_2 are constants which are independent of *R*. Furthermore, large bending losses tend to occur in multimode fibers at a critical radius of curvature R_c which may be estimated from:

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

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

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

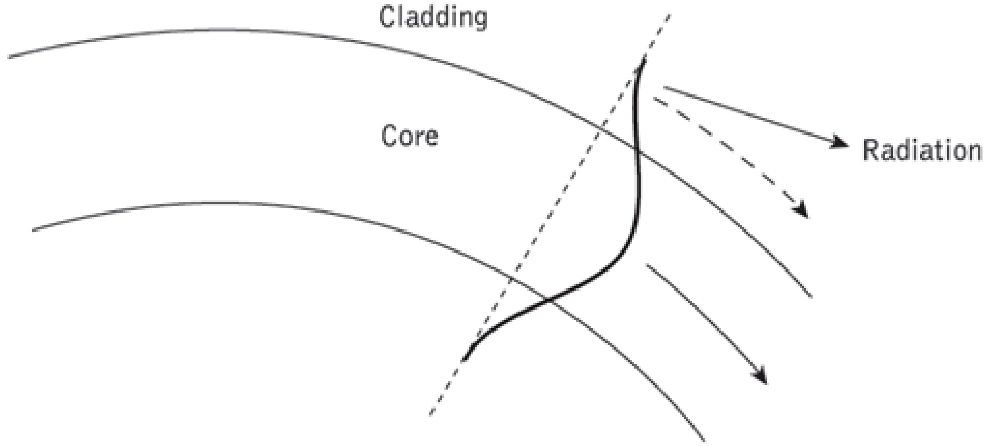


Figure 2.5 An illustration of the radiation loss at a fiber bend.

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

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

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

6. Describe the dispersion of single mode and multimode fiber. [CO2-L1]

Dispersion of single mode fiber

The pulse broadening in single-mode fibers results almost entirely from chromatic or intramodal dispersion as only a single-mode is allowed to propagate.* Hence the bandwidth is limited by the finite spectral width of the source. Unlike the situation in multimode fibers, the mechanisms giving chromatic dispersion in single-mode fibers tend to be interrelated in a complex manner. The transit time or specific group delay σg for a light pulse propagating along a unit length of single-mode fiber may be given as:

where *c* is the velocity of light in a vacuum, β is the propagation constant for a mode within the fiber core of refractive index *n*1 and *k* is the propagation constant for the mode in a vacuum. The total first-order dispersion parameter or the chromatic dispersion of a single-mode fiber, *D*T, is given by the derivative of the specific group delay with respect to the vacuum wavelength as:

$$D_T = \frac{d\tau_g}{d\lambda}$$

In common with the material dispersion parameter it is usually expressed in units of ps nm−1 km−1. When the variable is replaced by, then the total dispersion parameter becomes:

$$D_T = -\frac{\omega}{\lambda}\frac{d\tau_g}{d\omega} = -\frac{\omega}{\lambda}\frac{d^2\beta}{d\omega^2}$$

The fiber exhibits intramodal dispersion when varies nonlinearly with wavelength. may be expressed in terms of the relative refractive index difference and the normalized propagation constant *b* as

$$\beta = kn_1[1 - 2\Delta(1 - b)]^{\frac{1}{2}}$$

The rms pulse broadening caused by chromatic dispersion down a fiber of length *L* is given by the derivative of the group delay with respect to wavelength as

$$\text{Total rms pulse broadening} = \sigma_\lambda L \left| \frac{d\tau_g}{d\lambda} \right| = \frac{\sigma_\lambda L 2\pi}{c\lambda^2}\frac{d^2\beta}{dk^2}$$

where is the source rms spectral linewidth centered at a wavelength . When detailed calculation of the first and second derivatives with respect to *k* gives the dependence of the pulse broadening on the fiber material's properties and the normalized propagation constant *b*. This gives rise to three interrelated effects which involve complicated cross-product terms. However, the final expression may be separated into three composite dispersion components in such a way that one of the effects dominates each terms. The dominating effects are as follows:

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

$$D_W = -\left(\frac{n_1 - n_2}{\lambda c}\right) V \frac{d^2(Vb)}{dV^2}$$

- ✓ The material dispersion parameter D_M defined by. $\lambda/c \mid d^2n/d\lambda^2 \mid$ where $n = n_1$ or n_2 for the core or cladding respectively
  The waveguide dispersion parameter D_W, may be obtained from by which substitution □g, is defined as:

$$D_T = D_M + D_W + D_P \qquad (\text{ps nm}^{-1}\ \text{km}^{-1})$$

where V is the normalized frequency for the fiber. Since the normalized propagation constant b for a specific fiber is only dependent on V, then the normalized waveguide dispersion coefficient $V d^2(Vb)/dV^2$ also depends on V. This latter function is another universal parameter which plays a central role in the theory of single mode fibers.

A profile dispersion parameter D_P which is proportional to d□/d□

This situation is different from multimode fibers where the majority of modes propagate far from cutoff and hence most of the power is transmitted in the fiber core. In the multimode case the composite dispersion components may be simplified and separated into two chromatic terms which depend on either material or waveguide dispersion. Also, especially when considering step index multimode fibers, the effect of profile dispersion is negligible. Strictly speaking, in single-mode fiber with a power-law refractive index profile the composite dispersion terms should be employed.
Nevertheless, it is useful to consider the total first-order dispersion D_T in a practical single-mode fiber as comprising:

Dispersion of multi mode fiber

The overall dispersion in multimode fibers comprises both chromatic and intermodal terms. The total rms pulse broadening is given by:

$$\sigma_T = (\sigma_c^2 + \sigma_n^2)^{\frac{1}{2}}$$

where σ_c is the intramodal or chromatic broadening and σ_n is the intermodal broadening caused by delay differences between the modes (i.e. σ_s s for multimode step index fiber and σ_g for multimode graded index fiber). The chromatic term σ_c consists of pulse broadening due to both material and waveguide dispersion. However, since waveguide dispersion is generally negligible compared with material dispersion in multimode fibers, then $\sigma_c = \sigma_m$.

Unit-III

Fiber Optical Sources and Coupling

Part-A

1. Define direct band gap materials and indirect band gap materials. [CO3-L1]
In direct band gap materials direct transition is possible from valence band to conduction band.e.g.GaAs,InP,InGaAs In indirect band gap materials direct transition is not possible from valence band to conduction.e.g.silicon,germanium.

2. What are the advantages of LED? [CO3-L1]
1. LEDs are less complex circuits than Laser diodes.
2. Fabrication is easier.
3. They have long life.

3. What are the two types of confinement used in LEDs? [CO3-L1]
1. Optical confinement.
2. Carrier confinement.

4. What are the two types of LED configurations? [CO3-L1]
1. Homo junction
2. Single and double hetero junction.

5. What are the three requirements of Laser action? [CO3-L1]
1. Absorption
2. Spontaneous emission
3. Stimulated emission

6. What are the three types of Laser diode structures? [CO3-L1]
1. Gain indexed guide
2. Positive indexed guide
3. Negative indexed guide

7. What are the fundamental structures of Index guided lasers? [CO3-L1]
1. buried hetero structure.
2. Selectively diffused construction
3. Varying thickness structure
4. Bent layer configuration.

8. Define modulation. [CO3-L1]
The process of imposing information on a light stream is called modulation. This can be achieved by varying the laser drive current.

9. Define external quantum efficiency. [CO3-L1]
The external quantum efficiency is defined as the number of photons emitted per

radiative electron-hole pair recombination above threshold.

10. Define longitudinal modes. [CO3-L1]
Longitudinal modes are associated with the length of the cavity and determine the typical spectrum of the emitted radiation.

11. Define lateral modes[CO3-L1]
These modes lie in the plane of the pn junction. They depend on the sidewall preparation and the width of the cavity. It determines the shape of the lateral profile of the laser beam.

12. Define transverse modes. [CO3-L1]
Transverse modes are associated with the electromagnetic field and beam profile in the direction perpendicular to the plane of the pn junction. They determine the laser characteristics as the radiation pattern and the threshold current density.

13. Define internal quantum efficiency. [CO3-L1]
The internal quantum efficiency is the fraction of the electron-hole pairs that recombine radiatively. If the radiative recombination rate is R and the non-radiative recombination rate is Rnr, then the internal quantum efficiency is the ratio of the ratio of the radiative recombination rate to the total recombination rate.

14. Differentiate LEDs and Laser diodes[CO3-L2]

S.No.	LED	Laser diode
1	The output obtained is incoherent.	The output obtained is coherent.
2	Long lifetime.	Less lifetime.
3	Less expensive and less complex	More expensive and more complex.

15. Define quantum efficiency. [CO3-L1]
It is defined as the number of the electron – hole pairs generated per incident photon of energy hv and is given by
n=No.of electron-hole pairs
generated/No.of incident photons

16. What are techniques used in splicing? [CO3-L1]
1. Fusion splicing
2. V-groove splicing
3. Elastic tube splicing

17. Define fiber coupler. [CO3-L1]

An optical fiber coupler is a device that distributes light from a main fiber into one or more branch fibers

18. What are the requirements of a good connector? [CO3-L1]
The requirements of a good connector are as follows:

- Low loss
- Repeatability
- Predictability
- Ease of assembly and use
- Low cost & reliability
- Compatibility

19. What is meant by mechanical splice? [CO3-L1]
Mechanical splicing is one of the permanent joint techniques in which the fibers are held in alignment by some mechanical means.
Some of the methods are

a). The use of tubes around the fiber ends (tube splices)
b). V-grooves into which the butted fibers are placed (groove splices)

20. Mention the three types of fiber couplers. [CO3-L1]
a) Three and four port couplers
b) Star couplers
c) Wavelength division multiplexing devices

Part-B

1.Explain in detail about surface emitter LED and edge emitter LED Structure[CO3-L1]

Surface emitter LED

A method for obtaining high radiance is to restrict the emission to a small active region within the device. The technique pioneered by Burrus and Dawson with homostructure devices was to use an etched well in a GaAs substrate in order to prevent heavy absorption of the emitted radiation, and physically to accommodate the fiber. These structures have a low thermal impedance in the active region allowing high current densities and giving high-radiance emission into the optical fiber. Furthermore, considerable advantage may be obtained by employing DH structures giving increased efficiency from electrical and optical confinement as well as less absorption of the emitted radiation

This type of surface emitter LED (SLED) has been widely employed within optical fiber communications. The structure of a high-radiance etched well DH surface emitter* for the 0.8 to 0.9μm wavelength band is shown in Figure 3.2. The internal absorption in this device is very low due to the larger bandgap-confining layers, and the reflection coefficient at the back crystal face is high giving good forward radiance. The emission from the active layer is essentially isotropic, although the external emission distribution may be considered Lambertian with a beam width of 120° due to refraction from a high to a low refractive index at the GaAs–fiber interface. The power coupled *P*c into a multimode step index fiber may be estimated from the relationship:

$$P_c = \pi (1 - r) A R_D (NA)^2 \tag{3.1}$$

where *r* is the Fresnel reflection coefficient at the fiber surface, *A* is the smaller of the fiber core cross-section or the emission area of the source and *R*D is the radiance of the source.

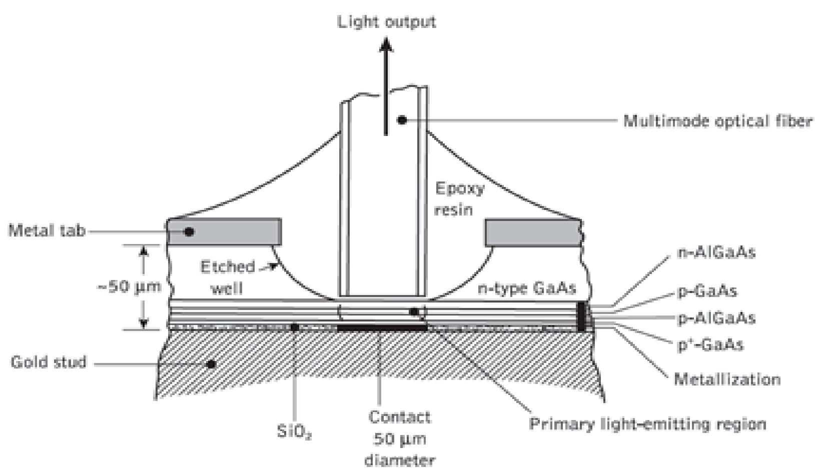


Figure 3.2 The structure of an AlGaAs DH surface-emitting LED (Burrus type).

However, the power coupled into the fiber is also dependent on many other factors including the distance and alignment between the emission area and the fiber, the SLED emission pattern and the medium between the emitting area and the fiber. For instance, the addition of epoxy resin in the etched well tends to reduce the refractive index mismatch and increase the external power efficiency of the device. Hence, DH surface emitters often give more coupled optical power than predicted by Eq. (3.1).

However, for graded index fiber optimum direct coupling requires that the source diameter be about one-half the fiber core diameter. In both cases lens coupling may give increased levels of optical power coupled into the fiber but at the cost of additional complexity. Other factors which complicate the LED fiber coupling are the transmission characteristics of the leaky modes or large angle skew rays. Much of the optical power from an incoherent source is initially coupled into these large-angle rays, which fall within the acceptance angle of the fiber but have much higher energy than meridional rays. Energy from these rays goes into the cladding and may be lost.

Hence much of the light coupled into a multimode fiber from an LED is lost within a few hundred meters. It must therefore be noted that the effective optical power coupled into a short length of fiber significantly exceeds that coupled into a longer length.

The planar structure of the Burrus-type LED and other nonetched well SLEDs allows significant lateral current spreading, particularly for contact diameters less than 25 μm. This current spreading results in a reduced current density as well as an effective emission area substantially greater than the contact area.

Edge emitter LED

Another basic high-radiance structure currently used in optical communications is the stripe geometry DH edge emitter LED (ELED). This device has a similar geometry to a conventional contact stripe injection laser, as shown in Figure 3.3.

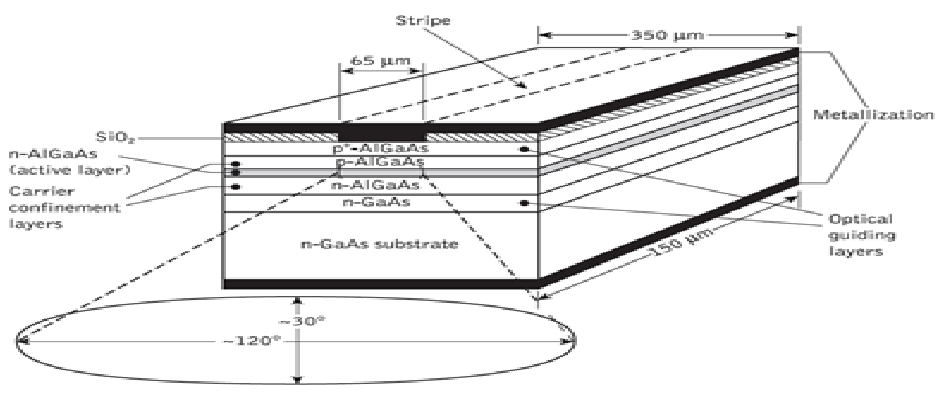


Figure 3.3 Schematic illustration of the structure of a stripe geometry DH AlGaAs edge-emitting LED

It takes advantage of transparent guiding layers with a very thin active layer (50 to 100 μm) in order that the light produced in the active layer spreads into the transparent guiding layers, reducing self-absorption in the active layer. The consequent waveguiding narrows the beam divergence to a half-power width of around 30° in the plane perpendicular to the junction. However, the lack of waveguiding in the plane of the junction gives a Lambertian output with a half-power width of around 120°, as illustrated in Figure3.3. Most of the propagating light is emitted at one end face only due to a reflector on the other end face and an antireflection coating on the emitting end face. The effective radiance at the emitting end face can be very high giving an increased coupling efficiency into small-*NA* fiber compared with the surface emitter. However, surface emitters generally radiate more power into air (2.5 to 3 times) than edge emitters since the emitted light is less affected by reabsorption and interfacial recombination. Comparisons have shown that edge emitters couple more optical power into low *NA* (less than 0.3) than surface emitters, whereas the opposite is true for large *NA* (greater than 0.3).

The enhanced waveguiding of the edge emitter enables it in theory to couple 7.5 times more power into low-*NA* fiber than a comparable surface emitter. However, in practice the increased coupling efficiency has been found to be slightly less than this (3.5 to 6 times). Similar coupling efficiencies may be achieved into low-*NA* fiber with surface emitters by the use of a lens. Furthermore, it has been found that lens coupling with edge emitters may increase the coupling efficiencies by comparable factors (around five times).

The stripe geometry of the edge emitter allows very high carrier injection densities for given drive currents. Thus it is possible to couple approaching a milliwatt of optical power into low-*NA* (0.14) multimode step index fiber with edge-emitting LEDs operating at high drive currents (500 mA).

Edge emitters have also been found to have a substantially better modulation bandwidth of the order of hundreds of megahertz than comparable surface-emitting structures with the same drive level. In general it is possible to construct edge-emitting LEDs with a narrower line width than surface emitters, but there are manufacturing problems with the more complicated structure (including difficult heat-sinking geometry) which moderate the benefits of these devices.

2. Explain detail about semiconductor injection Laser diode. [CO3-L1]

The electroluminescent properties of the forward-biased *p–n* junction diode have been considered in the preceding sections. Stimulated emission by the recombination of the injected carriers is encouraged in the semiconductor injection laser (also called the injection laser diode (ILD) or simply the injection laser) by the provision of an optical cavity in the crystal structure in order to provide the feedback of photons. This gives the injection laser several major advantages over other semiconductor sources (e.g. LEDs) that may be used for optical communications. These are as follows:

1. High radiance due to the amplifying effect of stimulated emission. Injection lasers will generally supply milliwatts of optical output power.
2. Narrow linewidth on the order of 1 nm (10 Å) or less which is useful in minimizing the

effects of material dispersion.

3. Modulation capabilities which at present extend up into the gigahertz range and will undoubtedly be improved upon.

4. Relative temporal coherence which is considered essential to allow heterodyne (coherent) detection in high-capacity systems, but at present is primarily of use in single-mode systems

5. Good spatial coherence which allows the output to be focused by a lens into a spot which has a greater intensity than the dispersed unfocused emission.

This permits efficient coupling of the optical output power into the fiber even for fibers with low numerical aperture. The spatial fold matching to the optical fiber which may be obtained with the laser source is not possible with an incoherent emitter and, consequently, coupling efficiencies are much reduced.

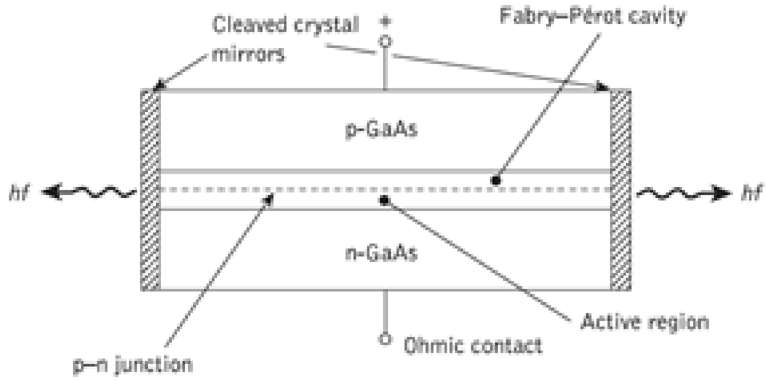


Figure 3.4 Schematic diagram of a GaAs homojunction injection laser with a Fabry–Pérot cavity

These advantages, together with the compatibility of the injection laser with optical fibers (e.g. size), led to the early developments of the device in the 1960s. Early injection lasers had the form of a Fabry–Pérot cavity often fabricated in gallium arsenide which was the major III–V compound semiconductor with electroluminescent properties at the appropriate wavelength for first-generation systems. The basic structure of this homojunction device is shown in Figure 3.4, where the cleaved ends of the crystal act as partial mirrors in order to encourage stimulated emission in the cavity when electrons are injected into the *p*-type region. However, as mentioned previously these devices had a high threshold current density (greater than 104 A cm−2) due to their lack of carrier containment and proved inefficient light sources.

High current densities required dictated that these devices when operated at 300 K were largely utilized in a pulsed mode in order to minimize the junction temperature and thus avert damage. Improved carrier containment and thus lower threshold current densities (around 103 A cm−2) were achieved using heterojunction structures.

The DH injection laser fabricated from lattice-matched III–V alloys provided both carrier and optical confinement on both sides of the *p–n* junction, giving the injection laser a greatly enhanced performance. This enabled these devices with the appropriate heat sinking to be operated in a CW mode at 300 K with obvious advantages for optical communications (e.g. analog transmission). However, in order to provide reliable CW operation of the DH injection laser it was necessary to provide further carrier and optical confinement which led to the introduction of stripe geometry DH laser configurations. Prior to discussion of this structure, however, it is useful to consider the efficiency of the semiconductor injection laser as an optical source.

Stripe geometry

The DH laser structure provides optical confinement in the vertical direction through the refractive index step at the heterojunction interfaces, but lasing takes place across the whole width of the device. This situation is illustrated in Figure 3.5 which shows the broad-area DH laser where the sides of the cavity are simply formed by roughening the edges of the device in order to reduce unwanted emission in these directions and limit the number of horizontal transverse modes. However, the broad emission area creates several problems including difficult heat sinking, lasing from multiple filaments in the relatively wide active area and unsuitable light output geometry for efficient coupling to the cylindrical fibers.

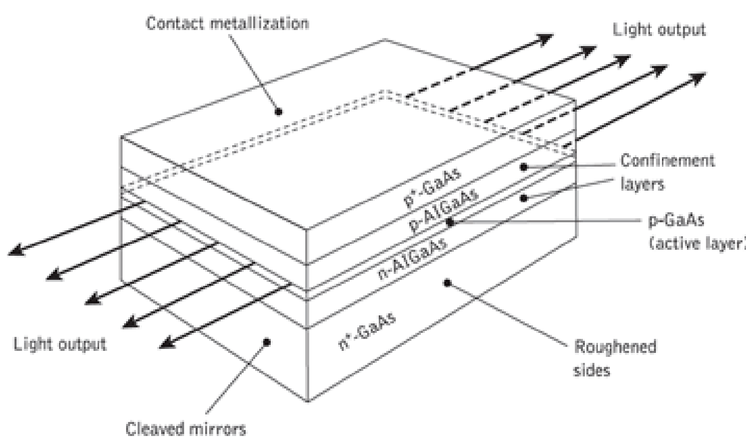


Figure 3.5 A broad-area GaAs/AlGaAs DH injection laser

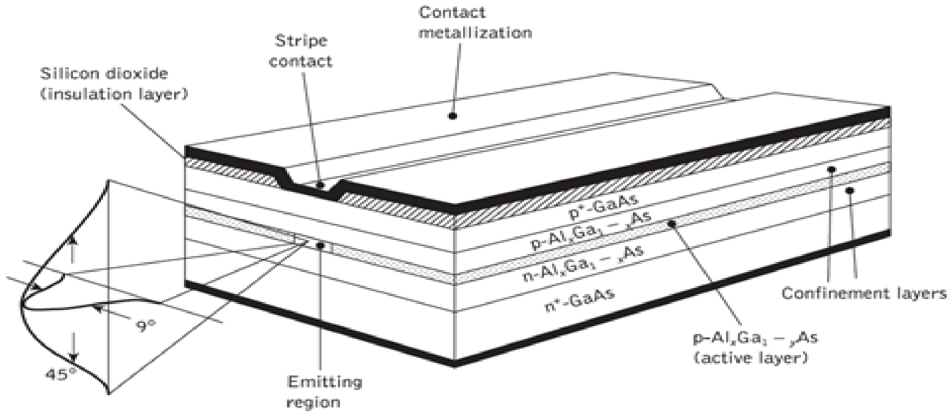


Figure 3.6 Schematic representation of an oxide stripe AlGaAs DH injection laser

To overcome these problems while also reducing the required threshold current, laser structures in which the active region does not extend to the edges of the device were developed. A common technique involved the introduction of stripe geometry to the structure to provide optical containment in the horizontal plane. The structure of a DH stripe contact laser is shown in Figure 3.6 where the major current flow through the device and hence the active region is within the stripe. Generally, the stripe is formed by the creation of high-resistance areas on either side by techniques such as proton bombardment or oxide isolation.

The stripe therefore acts as a guiding mechanism which overcomes the major problems of the broad-area device. However, although the active area width is reduced the light output is still not particularly well collimated due to isotropic emission from a small active region and diffraction within the structure. The optical output and far-field emission pattern are also illustrated in Figure 6.21. The output beam divergence is typically 45° perpendicular to the plane of the junction and 9° parallel to it. Nevertheless, this is a substantial improvement on the broad-area laser.

3. Describe the index guide Laser.

The drawbacks associated with the gain-guided laser structures were largely overcome through the development of index-guided injection lasers. In some such structures with weak index guiding, the active region waveguide thickness is varied by growing it over a channel or ridge in the substrate. A ridge is produced above the active region and the surrounding areas are etched close to it (i.e. within 0.2 to 0.3 μm). Insulating coatings on these surrounding areas confine the current flow through the ridge and active stripe while the edges of the ridge reflect light, guiding it within the active layer, and thus forming a waveguide. Hence in the ridge waveguide laser shown in Figure 3.9 (a), the ridge not only provides the location for the weak index guiding but also acts as the narrow current confining stripe. These devices have been fabricated to operate at various wavelengths with a single lateral mode, and room temperature CW threshold currents as low as 18 mA with output powers of 25 mW have been reported.

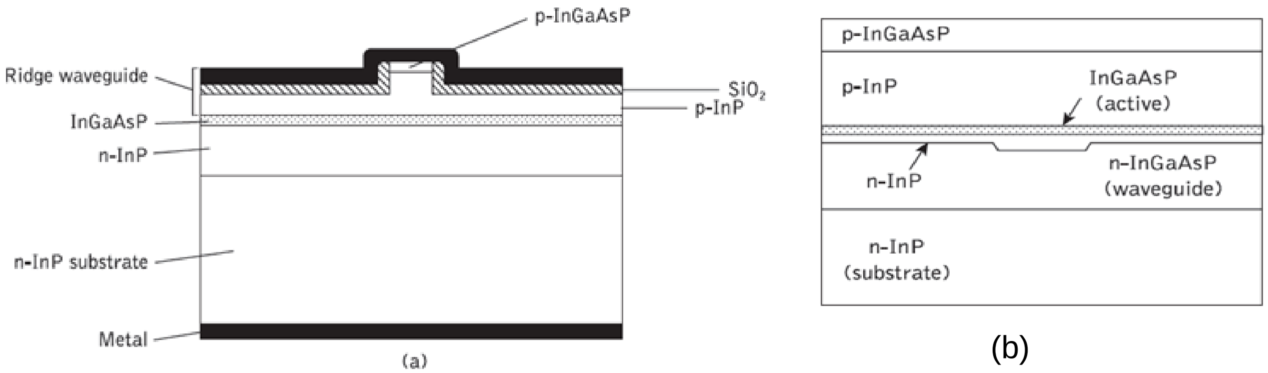


Figure 3.9 Index-guided lasers: (a) ridge waveguide injection laser structures; (b) rib (plano-convex) waveguide injection laser structure

More typically, the threshold currents for such weakly index-guided structures are in the range 40 to 60 mA, which compares a light output versus current characteristic for a ridge waveguide laser with that of an oxide stripe gain-guided device. Alternatively, the application of a uniformly thick, planar active waveguide can be achieved through lateral variations in the confinement layer thickness or the refractive index. However, room temperature CW threshold currents are between 70 and 90 mA with output powers of around 20 mW for InGaAsP devices operating at a wavelength of 1.3 μm

4. Explain detail about fiber splicing and Explain fusion and mechanical splicing. [CO3-L1]

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. 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

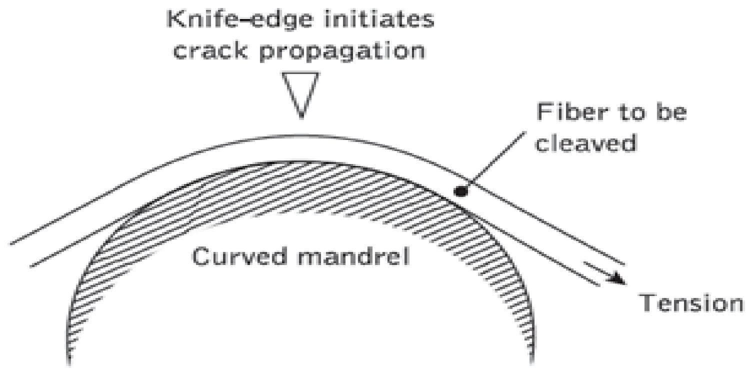


Figure 2.20 Optical fiber end preparation: the principle of scribe and break cutting

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 2.20. 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 2.20 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.

A schematic diagram of the basic arc fusion method is given in Figure 2.21(a) illustrating how the two fibers are welded together. Figure 2.21(b) shows a development of the basic arc fusion process which involves the rounding of the fiber ends with a low-energy discharge before pressing the fibers together and fusing with a stronger arc.

This technique, 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.

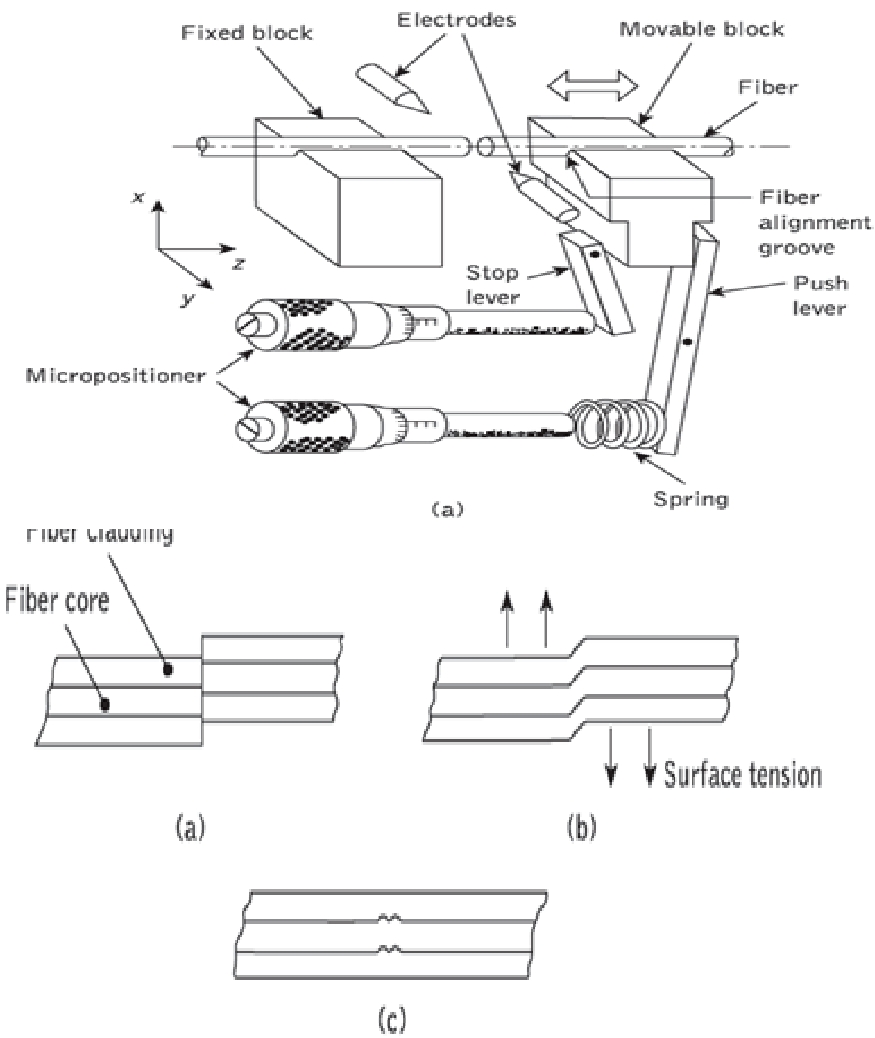


Figure 2.21 Electric arc fusion splicing: (a) an example of fusion splicing apparatus; (b) schematic illustration of the prefusion method for accurately splicing optical fibers

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.

Self-alignment, illustrated in Figure 2.22, 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.

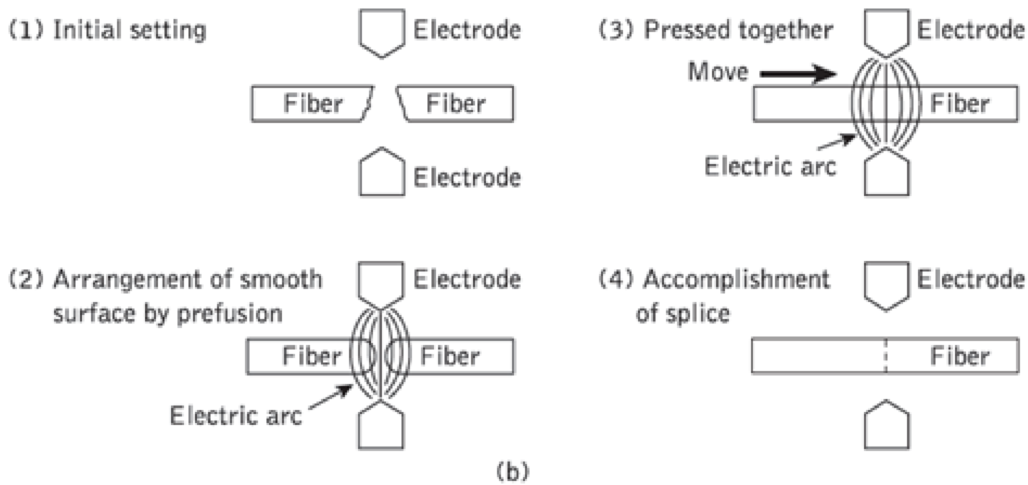


Figure 2.22 Self-alignment phenomenon which takes place during fusion splicing: (a) before fusion; (b) during fusion; (c) after fusion

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 2.23(a) 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 2.23(b). 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 2.23(b). Mean splice insertion losses of 0.073 dB have been achieved using multimode graded index fibers with the loose tube approach.

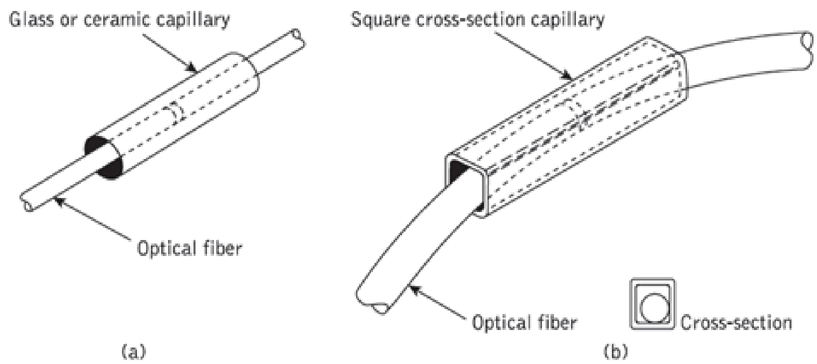


Figure 2.23 Techniques for tube splicing of optical fibers: (a) snug tube splice; (b) loose tube splice utilizing square cross-section capillary

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 2.24(a) 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.

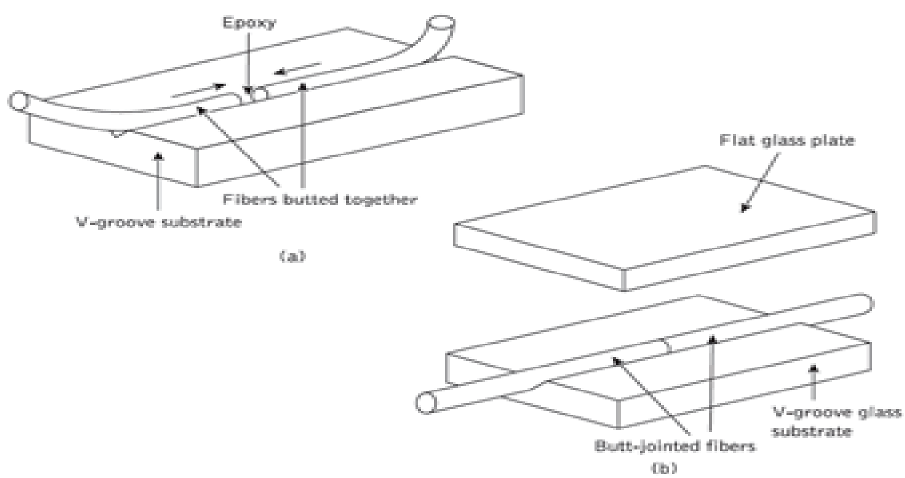


Figure 2.24 V-groove splices

V-groove splices formed by sandwiching the butted fiber ends between a V-groove glass substrate and a flat glass retainer plate, as shown in Figure 2.24(b), 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 in Figure 2.25. 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.

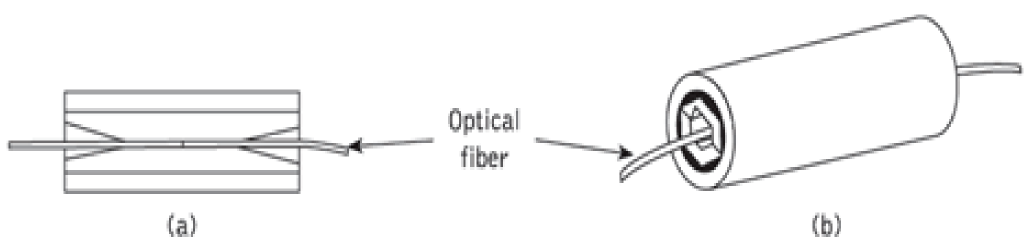


Figure 2.25 The elastomeric splice: (a) cross-section; (b) assembly

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 2.26(a). An elastic element (a spring) was used to press the fibers into a groove and maintain the fiber end alignment, as illustrated in Figure 2.26(b). 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.

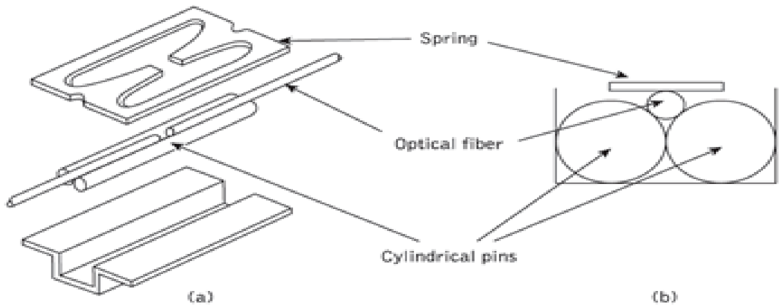


Figure 2.26 The Springroove splice: (a) expanded overview of the splice; (b) schematic cross-section of the splice

An example of a secondary aligned mechanical splice for multimode fiber is shown in Figure 2.27. 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.

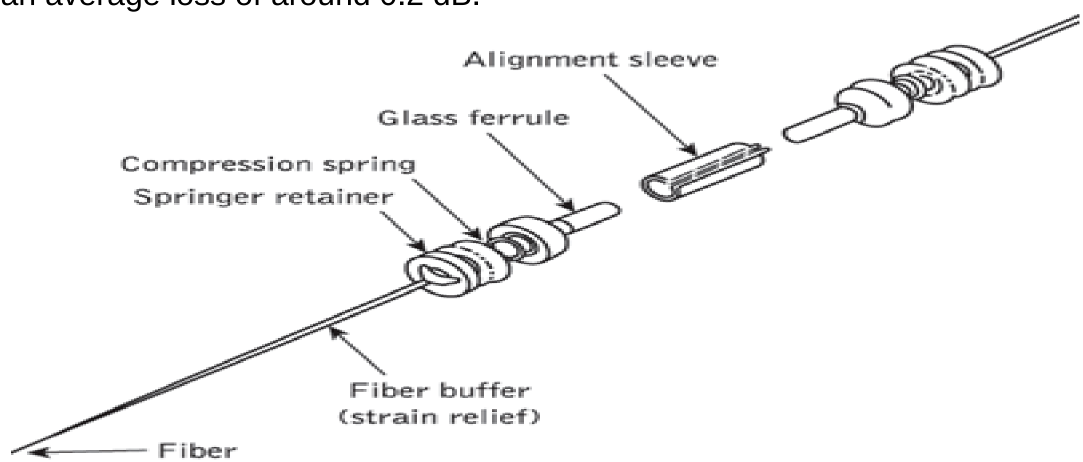


Figure 2.27 Multimode fiber mechanical splice using glass capillary tube

5. Discuss expanded beam connectors and cylindrical ferrule connectors[CO3-L2]

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 which, in the example shown in Figure 2.29(a), is a spring.

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:

- ✓ leaving 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 2.29(b). 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 losses in the range 1 to 2 dB with multimode step index fibers

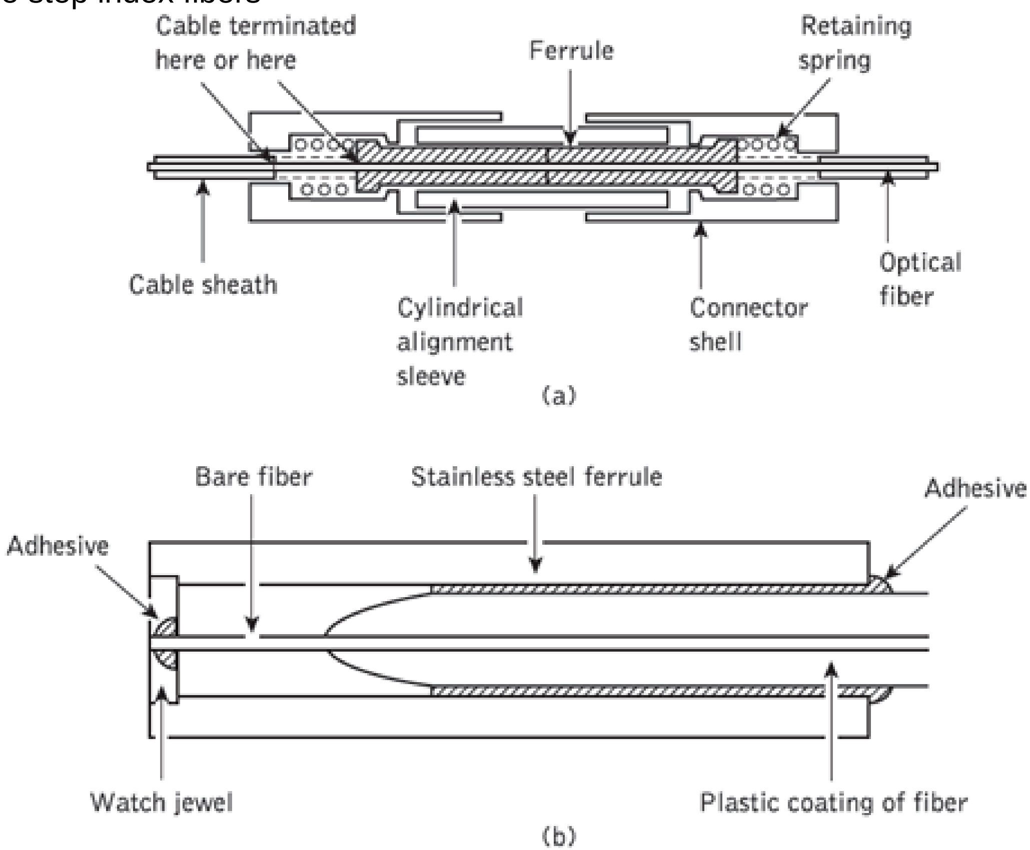


Figure 2.29 Ferrule connectors: (a) structure of a basic ferrule connector; (b) structure of a watch jewel connector ferrule

Expanded beam connectors

An alternative to connection via direct butt joints between optical fibers is offered by the principle of the expanded beam. Fiber connection utilizing this principle is illustrated in Figure 2.30, which shows a connector consisting of two lenses for collimating and refocusing the light from one fiber into the other.

The use of this interposed optics makes the achievement of lateral alignment much less critical than with a butt-jointed fiber connector.

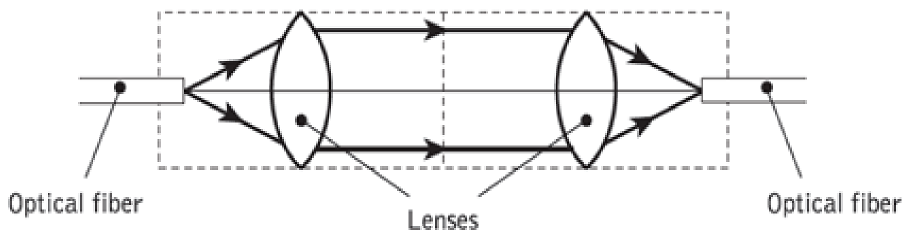


Figure 2.30 Schematic illustration of an expanded beam connector showing the principle of operation

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 multi fiber 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 2.31. The connector shown in Figure 2.31(a) 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 2.31(b) 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.

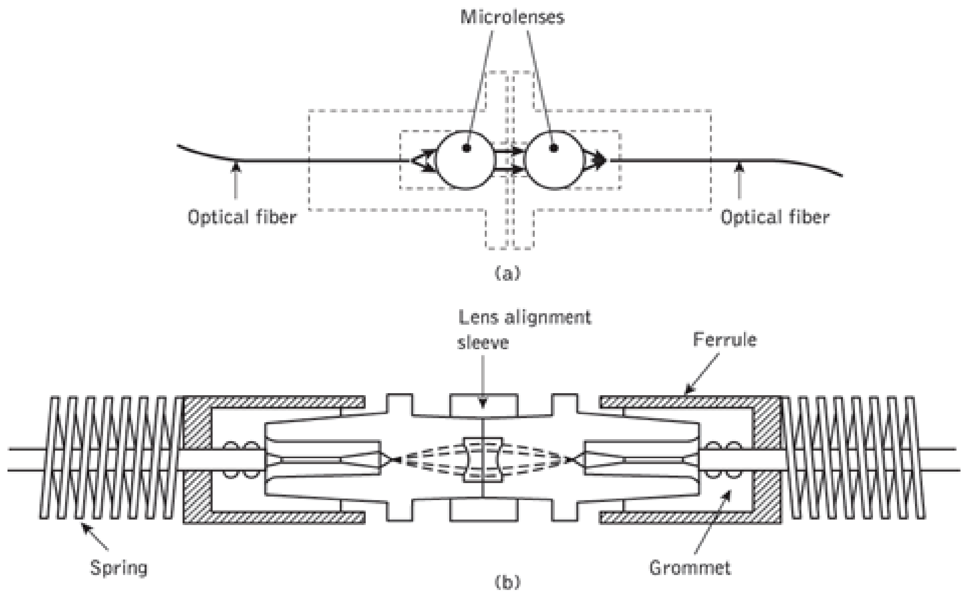


Figure 2.31 Lens-coupled expanded beam connectors: (a) schematic diagram of a connector with two microlenses making a 1:1 image of the emitting fiber upon the receiving one; (b) molded plastic lens connector assembly

Unit-IV

Fiber Optic Receiver and Measurements

Part- A

1. Define minimum detectable optical power. [CO4-L1]

It is defined as the optical power necessary to produce a photocurrent of the same magnitude as the root mean square of the total current.

2. Define quantum noise. [CO4-L1]

It is not possible to predict exactly how many electron-hole pairs are generated by a known optical power incident on the detector is the origin of the type of short noise called quantum noise.

3. What is meant by error rate? [CO4-L1]

An approach is to divide the number Ne of errors occurring over a certain time interval t by the number Nt of pulses transmitted during this interval. This is called either the error rate or the bit error rate.

$$BER = Ne/ Nt = Ne/Bt$$

Where $B= 1/ Tb$

4. Define quantum limit[CO4-L1]

- ✓ Low impedence(LZ) preamplifier
- ✓ High impedence(HZ) preamplifier
- ✓ Transimpedence preamplifier

6. What is meant by excess noise factor? [CO4-L1]

The ratio of the actual noise generated in an avalanche photodiode to the noise that would exist if all carrier pairs were multiplied by exactly m is called the excess noise factor (F).

7. What is meant by inter symbol interference (ISI)? [CO4-L1]

ISI results from pulse spreading in the optical fiber. The presence of this energy in adjacent time slots results in an interfering signal. Hence it is called ISI.

8. Give the advantages of Pin photodiodes. [CO4-L1]

- ✓ Very low reverse bias is necessary
- ✓ High quantum efficiency
- ✓ Large bandwidth
- ✓ Low noise level

9. What do you mean by thermal noise? [CO4-L1]

Thermal noise is due to the random motion of electrons in a conductor. Thermal noise arising from the detector load resistor and from the amplifier electronics tend to dominate in applications with low signal to noise ratio.

10. What is current mode of operation of photodiode? [CO4-L1]

In photo conducting mode, the photocurrent is slightly dependent on the reverse bias. For a constant reverse bias, the current is linear. This is called current mode of operation of the photodiode.

11. What are the system requirements? [CO4-L1]

The following are the key system requirements.

- The desired or possible transmission distance
- The data rate or channel bandwidth
- Bit error rate (BER)

12. Give the 2 analysis that are used to ensure system performance[CO4-L1]

The 2 analysis that are used to ensure system performance are:

- Link power budget analysis
- Rise time budget analysis

13. Give the range of system margin in link power budget? [CO4-L1]

The system margin is usually (6-8) db. A positive system margin ensures proper operation of the circuit. A negative value indicates that insufficient power will reach the detector to achieve the required bit error rate, BER.

14. What are the measures to avoid modal noise? [CO4-L1]

The measures are

- use LEDs
- use LASER having more longitudinal modes
- use a fiber with large numerical aperture
- use a single mode fiber

15. What is reflection noise? [CO4-L1]

It is the optical power that gets reflected at the refractive index discontinuities such as in splices, couplers and filters, or connectors. The reflected signals can degrade both the transmitter and receiver performance.

16. What are the effects of reflection noise in high speed systems? [CO4-L1]

They cause optical feedback which leads to optical instabilities that may lead to inter symbol interference and intensity noise.

17. Define modal noise? [CO4-L1]

It arises when the light from a coherent laser is coupled in to a multimode fiber operating at 400Mbps and higher. It mainly occurs due to mechanical vibrations and fluctuations in the frequency of the optical source.

18. What are the noise effects on system performance? [CO4-L1]

The main penalties are modal noise, wavelength chirp, spectral broadening, mode-partition noise.

19. Why the attenuation limit curve slopes downwards to the right? [CO4-L1]

As the minimum optical power required at the receiver for a given BER becomes higher for increasing data rates, the attenuation limit curve slopes downward to the right.

20. What are the system components of system rise time? [CO4-L1]

The 4 basic system components that contribute to the system rise time are:

- Transmitter (source) rise time
- Receiver rise time
- Material dispersion time of the fiber
- Modal dispersion time of the fiber link

All these 4 basic elements may significantly limit system speed

Part – B

1. Explain in detail about Total fiber attenuation and fiber absorption loss measurement. [CO4-L1]

Total fiber attenuation measurement

A commonly used technique for determining the total fiber attenuation per unit length is the cut-back or differential method. Figure 4.5 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.

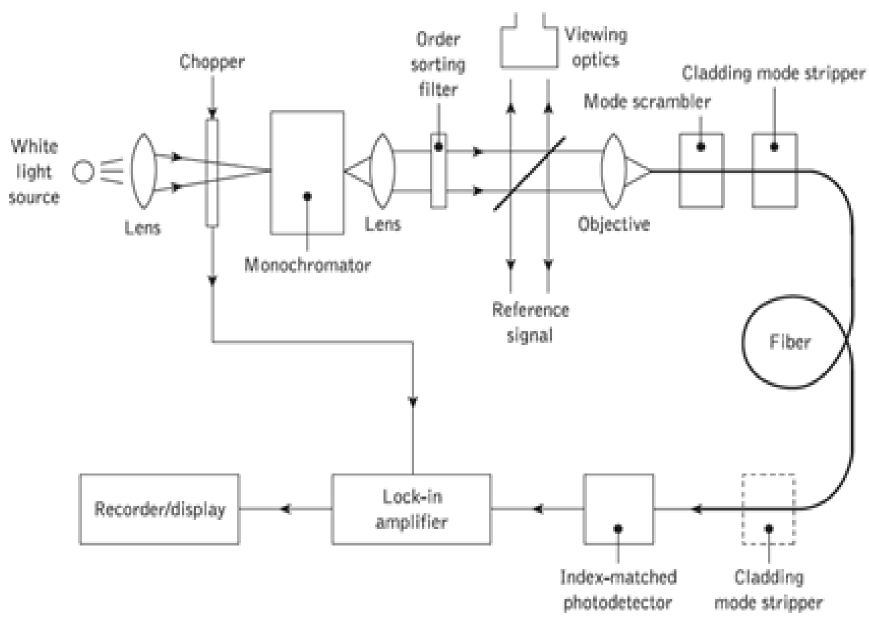


Figure 4.5 A typical experimental arrangement for the measurement of spectral loss in optical fibers using the cut-back technique

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 2 m from the input end and, maintaining the same launch conditions, another set of power output measurements is taken. 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.

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

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 4.6, which 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 4.6(b), has been widely adopted for absorption loss measurements.

The two fiber samples shown in Figure 4.6(b) 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 4.6(a). 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

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

passing known electrical power through one. Independent measurements can then be made using the calorimetric technique and with electrical measurement instruments.

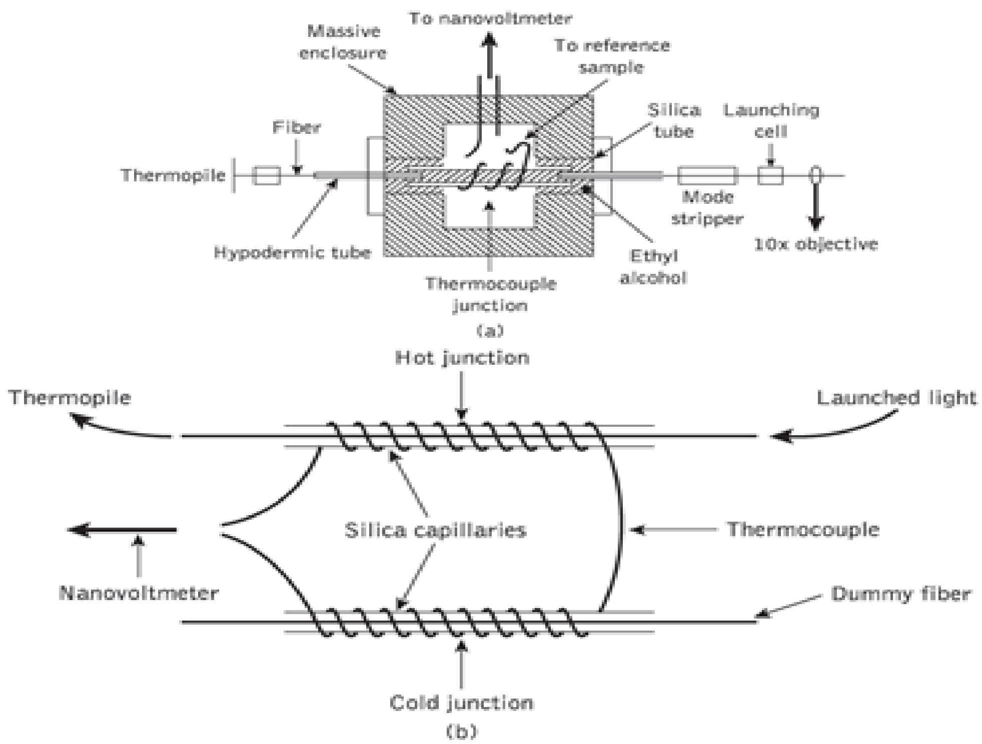


Figure 4.6 Calorimetric measurement of fiber absorption losses: (a) schematic diagram of a version of the apparatus; (b) the temperature measurement technique using a thermocouple

The calorimetric measurements provide the heating and cooling curve for the fiber sample used. A typical example of this curve is illustrated in Figure 4.7(a). The attenuation of the fiber due to absorption αabs may be determined from this heating and cooling characteristic. A time constant *t*c can be obtained from a plot of ($T_\infty - T_t$) on a logarithmic scale against the time *t*, an example of which shown in Figure 4.7(c) was obtained from the heating characteristic displayed in Figure 4.7(b). T_∞ corresponds to the maximum temperature rise of the fiber under test and *Tt* is the temperature rise at a time *t*.

It may be observed from Figure 4.7(a) that *T*∞ 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 4.7(c) as:

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

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.

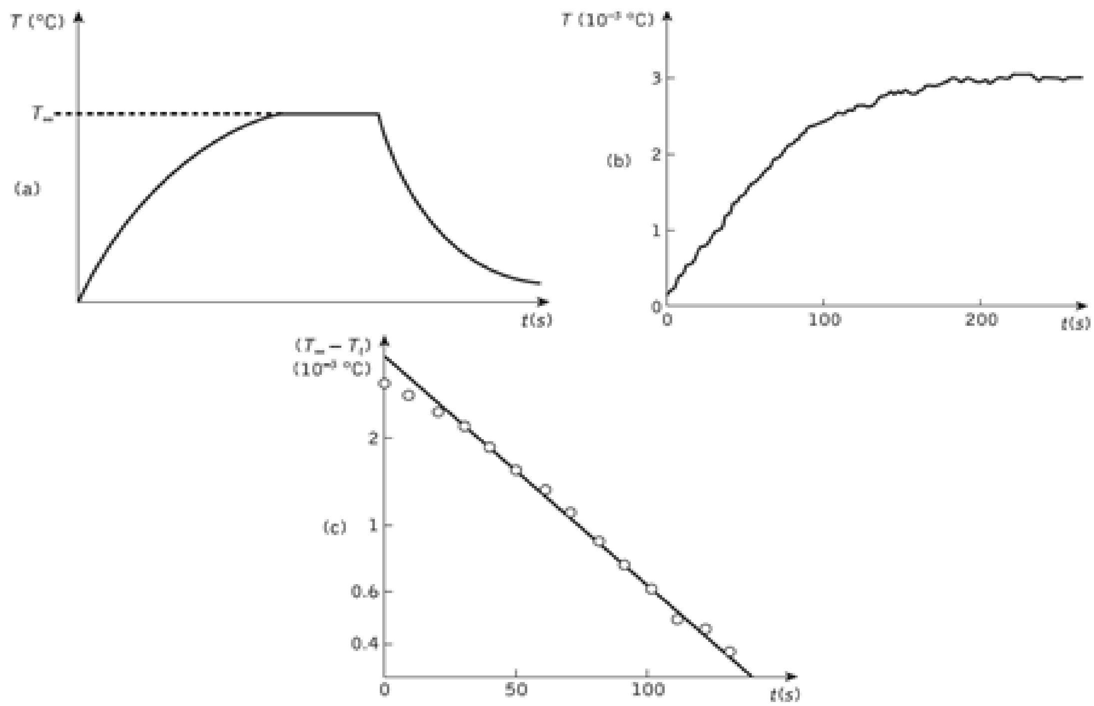


Figure 4.7 (a) A typical heating and cooling curve for a glass fiber sample. (b) A heating curve. (c) The corresponding plot of ($T_\infty - T_t$) against time for a sample glass rod

2.Explain in detail about Fiber scattering loss measurement and Fiber dispersion Measurements. [CO4-L1]

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 4.8. 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 indexmatching 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.

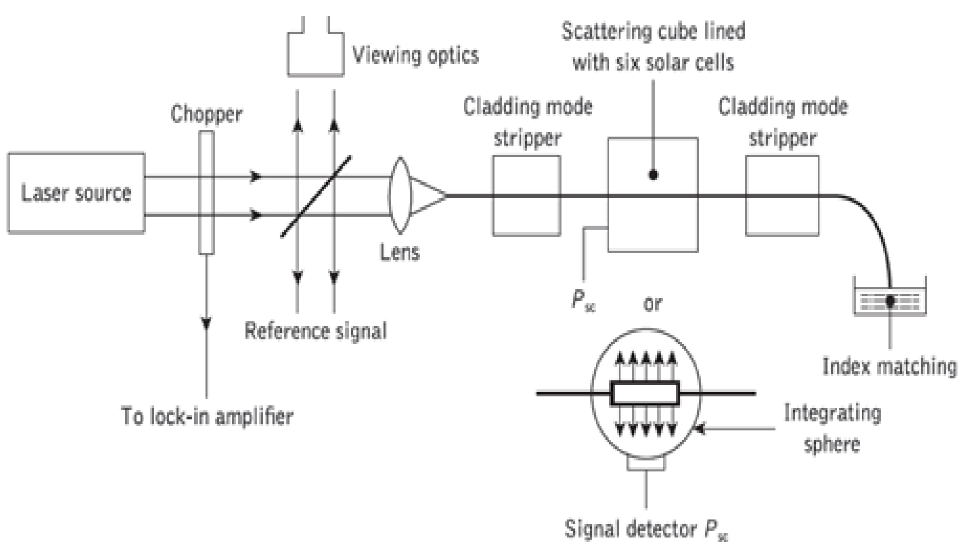


Figure 4.8 An experimental setup for measurement of fiber scattering loss illustrating both the solar cell cube and integrating sphere scattering cells

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. 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:

$$\alpha_{sc} = \frac{4.343 \times 10^5}{l(\text{cm})}\left(\frac{V_{sc}}{V_{opt}}\right) \text{dB km}^{-1} \tag{4.3}$$

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 Eq. (4.3) may be expanded to give:

$$\alpha_{sc} = \frac{10}{l(\text{km})}\log_{10}\left(\frac{P_{opt}}{P_{opt} - P_{sc}}\right) \text{dB km}^{-1} \tag{4.4}$$

Since the measurements of length are generally in centimeters and the optical power is normally registered in volts, Eq. (4.4) can be written as:

$$\alpha_{sc} = \frac{4.343}{l(\text{km})}\left(\frac{P_{sc}}{P_{opt}}\right) \text{dB km}^{-1} \tag{4.5}$$

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 in Section 3.8, 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 (i.e. intramodal dispersion). 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 $P_i(t)$ as:

$$P_o(t) = h(t) * P_i(t) \quad (4.6)$$

where the asterisk * denotes convolution. The convolution of $h(t)$ with $P_i(t)$ shown in Eq. (4.6) may be evaluated using the convolution integral where:

$$P_o(t) = \int_{-\infty}^{\infty} P_i(t-x)h(x)\,dx \quad (4.7)$$

In the frequency domain the power transfer function $H(\square)$ is the Fourier transform of $h(t)$ and therefore by taking the Fourier transforms of all the functions in Eq. (4.6) we obtain:

$$\mathcal{P}_o(\omega) = H(\omega)\mathcal{P}_i(\omega) \quad (4.8)$$

3. Discuss fiber numerical aperture measurements. [CO4-L1]

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 singlemode region) which has consequent effects on both the fiber dispersion (i.e. intermodal) and, possibly, the fiber attenuation (i.e. differential attenuation of modes). The numerical aperture (NA) is defined for a step index fiber as:

$$NA = \sin\theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}} \quad (4.17)$$

where θ_a is the maximum acceptance angle, n_1 is the core refractive index and n_2

is the cladding refractive index.

It is assumed that the light is incident on the fiber end face from air with a refractive index (n_0) of unity. Although Eq. (4.17) 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.

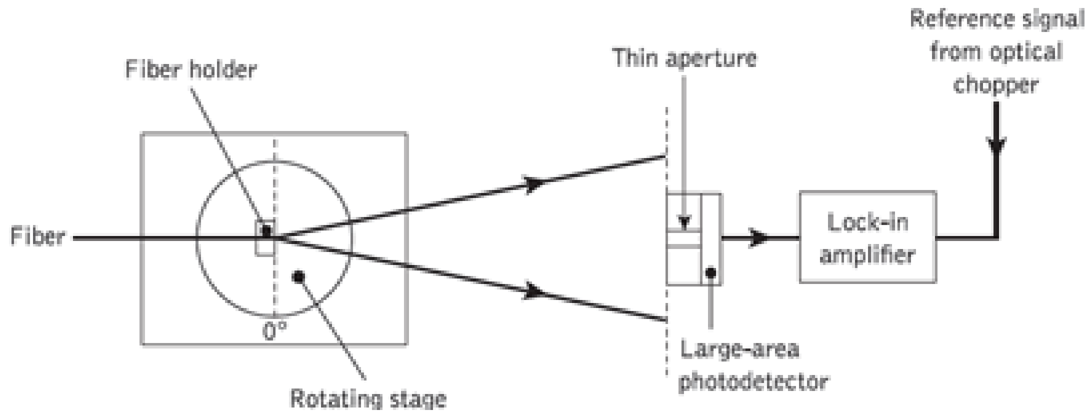


Figure 4.18 Fiber numerical aperture measurement using a scanning photo detector and a rotating stage

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:

$$NA(r) = \sin\theta_a(r) = (n_1^2(r) - n_2^2)^{\frac{1}{2}} \qquad (4.18)$$

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 4.18. A 2 m length of the graded index fiber has its faces prepared in order to ensure square smooth terminations.

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

The photodetector, which may be either a small-area device or an apertured large-area device, is placed 10 to 20 cm from the fiber and positioned in order to obtain a maximum signal with no rotation (0°). Hence when the rotating stage is turned the limits of the far-field pattern may be recorded. The output power is monitored and plotted as a function of angle, the maximum acceptance angle being obtained when the power drops to 5% of the maximum intensity. Thus the numerical aperture of the fiber can be obtained from Eq. (4.17).

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 4.19.

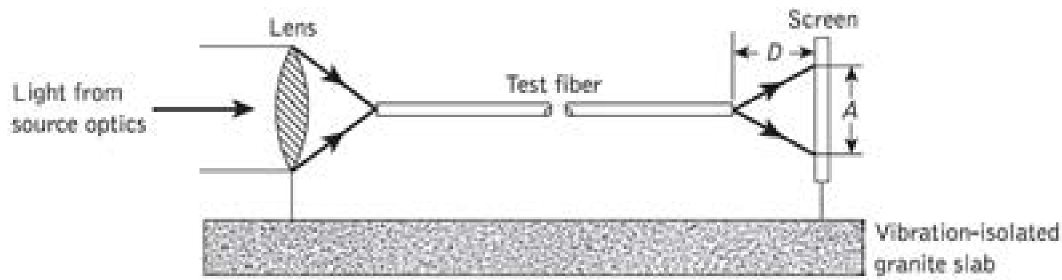


Figure 4.19 Apparatus for trigonometric fiber numerical aperture measurement

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 farfield 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:

$$NA = \sin\theta_a = \frac{A/2}{[(A/2)^2 + D^2]^{\frac{1}{2}}} = \frac{A}{(A^2 + 4D^2)^{\frac{1}{2}}} \qquad (4.19)$$

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.

4. Describe the fiber diameter measurements. [CO4-L2]

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 ms $^{-1}$). Use is therefore made of noncontacting optical methods such as fiber image projection and scattering pattern analysis.

The most common on-line measurement technique uses fiber image projection (shadow method) and is illustrated in Figure 4.20. 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 4.20 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 d□/d*t* following:

$$\frac{ds}{dt} = l\frac{d\phi}{dt} \qquad (4.20)$$

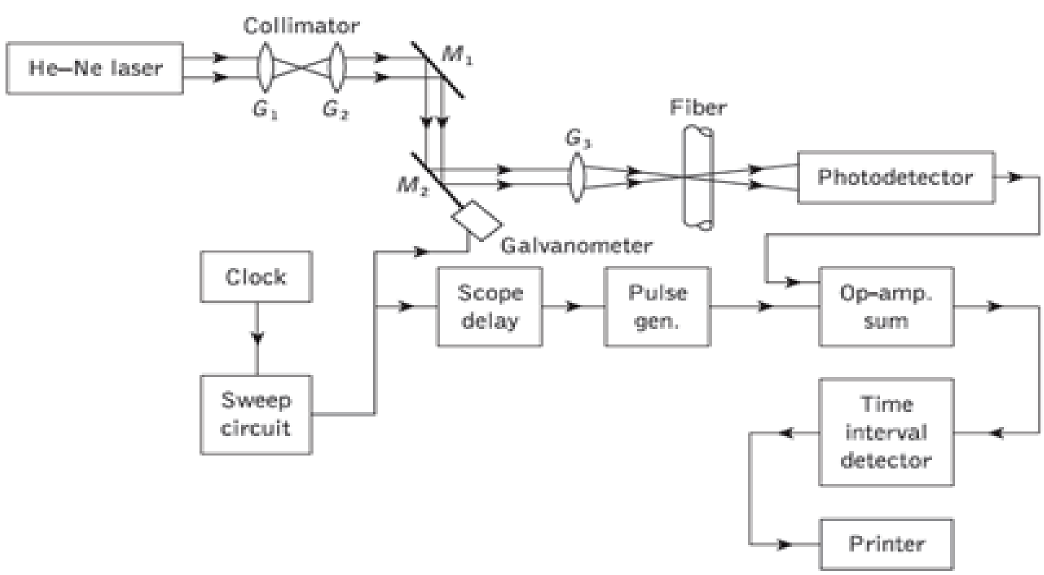


Figure 4.20 The shadow method for the on-line measurement of the fiber outer diameter.

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:

$$d_o = W_e \frac{ds}{dt} \tag{4.21}$$

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.

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.

Unit-V

Optical Networks and System Transmission

Part- A

1. What are the basic performances of the WDM? [CO5-L1]
- Insertion loss
- Channel width
- Cross talk

2. What are the techniques to reduce optical feedback? [CO5-L1]
- Fiber end faces with a curved surface to the laser emitting facet. Index matching oil or gel at air glass interfaces.
- PC connectors
- Optical isolators within the transmitter module.

3. What is WDM? [CO5-L1]
WDM is wavelength division multiplexing. The optical beam consists of different wavelengths and several channel information is transmitted over a single channel.

4. What is meant as bidirectional WDM? [CO5-L1]
A single WDM which operates as both multiplexing and De multiplexing Devices is said as the bidirectional WDM.

5. Define Radiance. [CO5-L1]
Radiance (or brightness) is a measure, in Watts, of the optical power radiated into a unit solid angle per unit area of the emitting surface.

6. What is meant by 'population inversion'? [CO5-L1]
In thermal equilibrium, the density of excited electrons is very small. Most photons incident on the system will therefore be absorbed, so that stimulated emission is essentially negligible. Stimulated emission will exceed absorption only if the population of the excitedstates is greater than that of the ground state. This condition is known as population inversion.

7. What are the factors to be considered in link power budget? [CO5-L1]
The factors to be considered in link power budget are:
- Transmission speed
- Optical sources & detectors
- Optical fiber

8. What are the causes of absorption? [CO5-L1]

Normally, the system is in the ground state. When a photon of energy $h\gamma_{12}$ impinges on the system, an electron in state E_1 can absorb the photon energy & be excited to state E_2.

9. What is meant by hetero junction? [CO5-L1]

In hetero junction, two different alloy layers are on each side of the active region. Because of the sandwich structure of differently composed alloy layers, both the carriers & optical field are confined in the central active layer.

10. What is meant by indirect band gap semiconductor material? [CO5-L1]

For indirect band gap materials, the conduction-band minimum & the valence- band maximum energy levels occur at different values of momentum. Here, band-to- band recombination must involve a third particle to conserve momentum, since the photon momentum is very small. Phonons serve this purpose.

11. What is meant by 'modal noise'? [CO5-L1]

It arises when light from a laser is coupled into the multimode fiber.

12. .What is the necessity of cladding for an optical fiber?[CO5-L1]

a) To provide proper light guidance inside the core
b) To avoid leakage of light from the fiber
c) To avoid mechanical strength
d) To protect the core from scratches and other mechanical damages for the fiber

Part-B

1. Explain in detail about SONET/SDH. [CO5-L1]

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

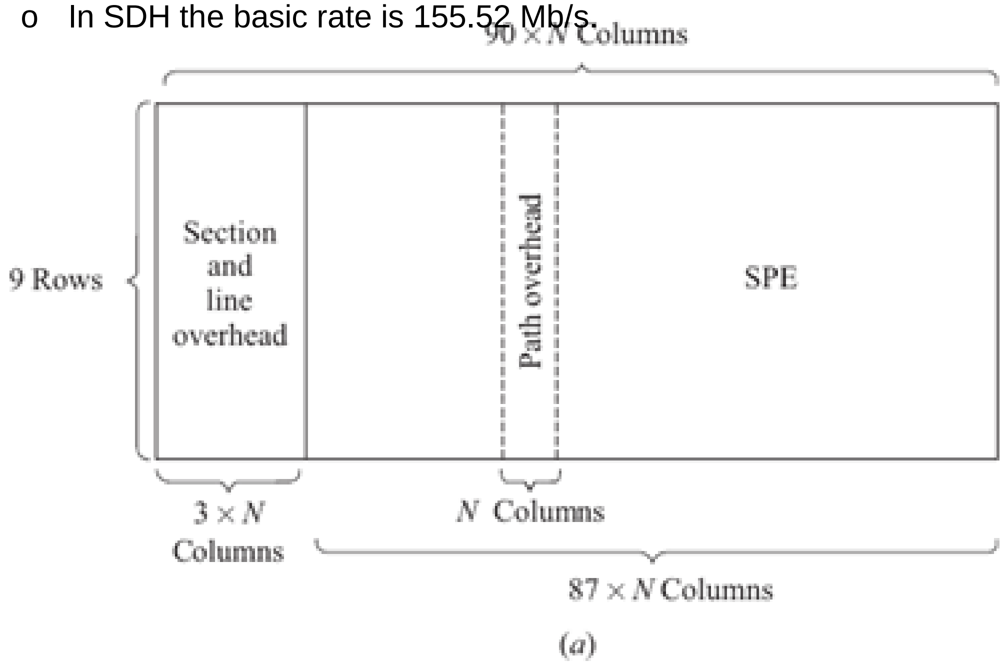


Figure 5.1 Basic formats of an STS-N SONET frame

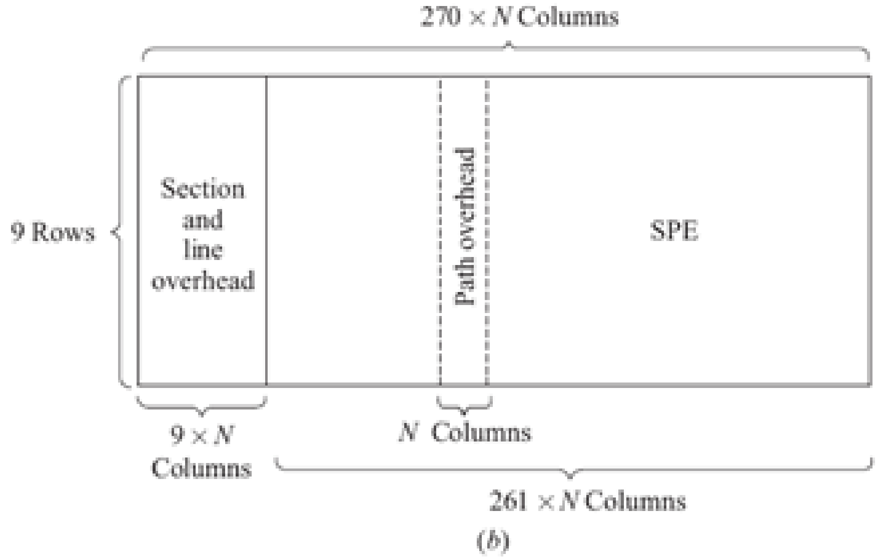


Figure 5.2 Basic formats of an STM-N SDH frame

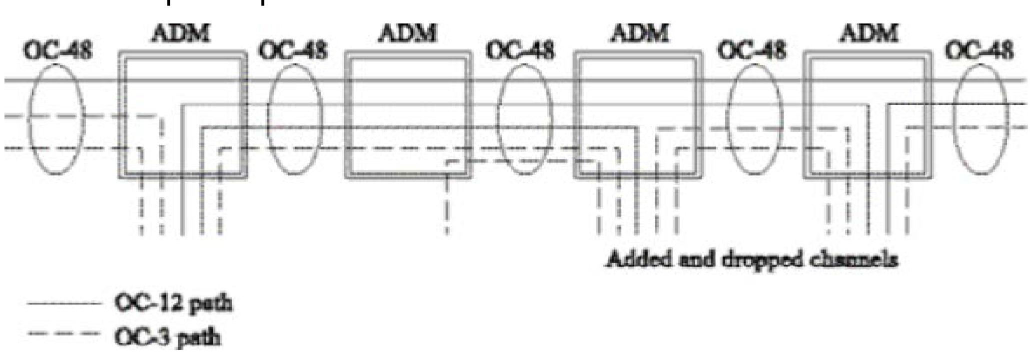
Common values of OC-N and STM-N:

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

SONET Add Drop Multiplexers:



SONET ADM is a fully synchronous, byte oriented device, that can be used add/drop OC sub-channels within an OC-*N* signal
Ex: OC-3 and OC-12 signals can be individually added/dropped from an OC-48 carrier

SONET/SDH Rings:

SONET and SDH can be configured as either a ring or mesh architecture
SONET/SDH rings are self-healing rings because the traffic flowing along a certain pathcan 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)

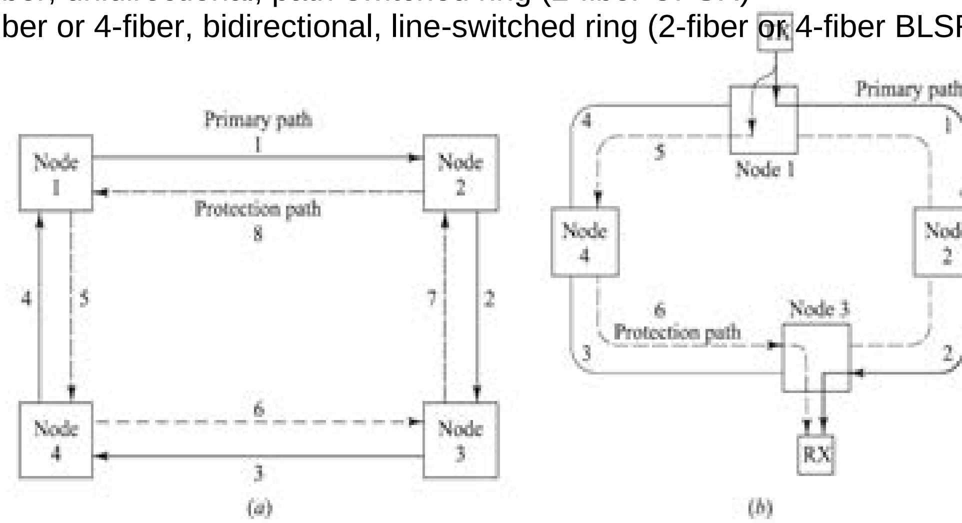
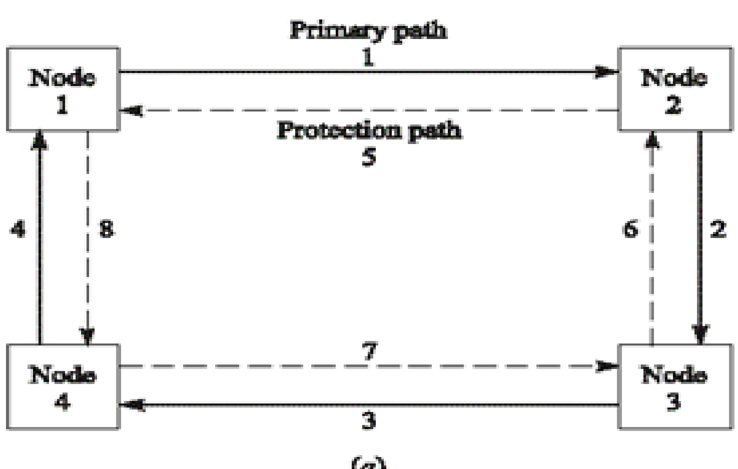


Figure 5.3 Generic 2-fiber UPSR with a counter-rotating protection path

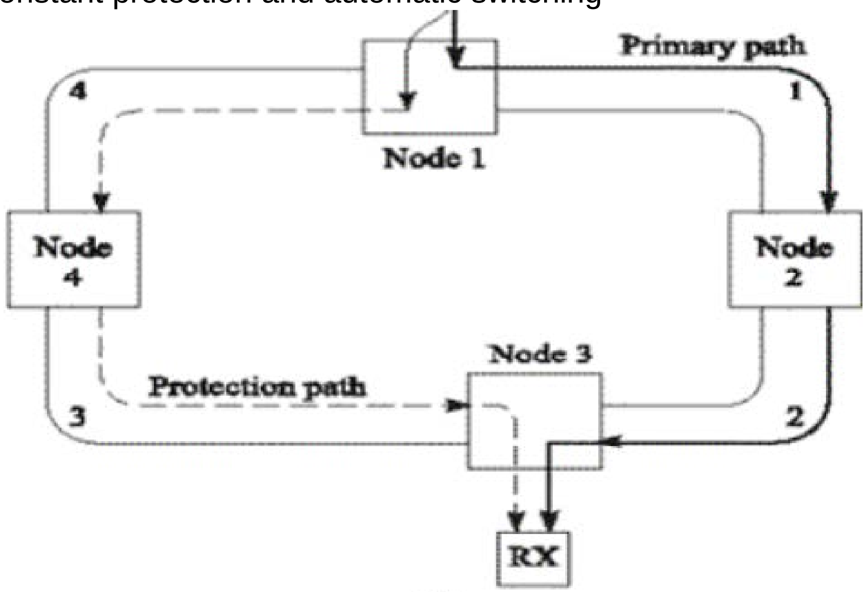
2-Fiber UPSR Basics:



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:

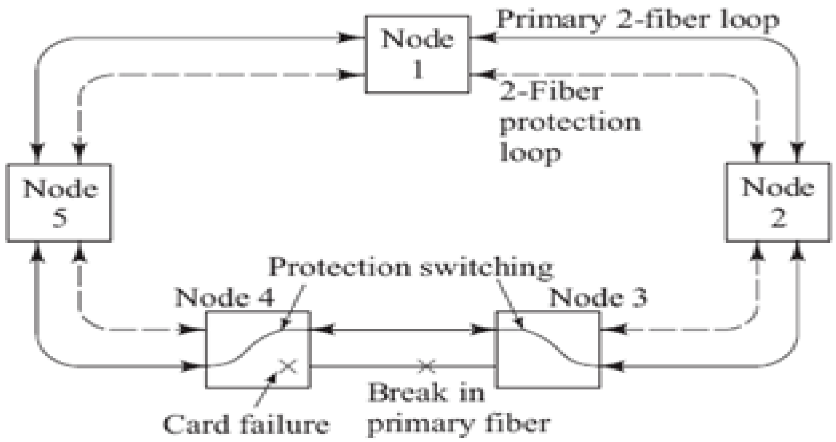
- Rx compares the signals received via the primary and protection paths and picks the best one
- Constant protection and automatic switching



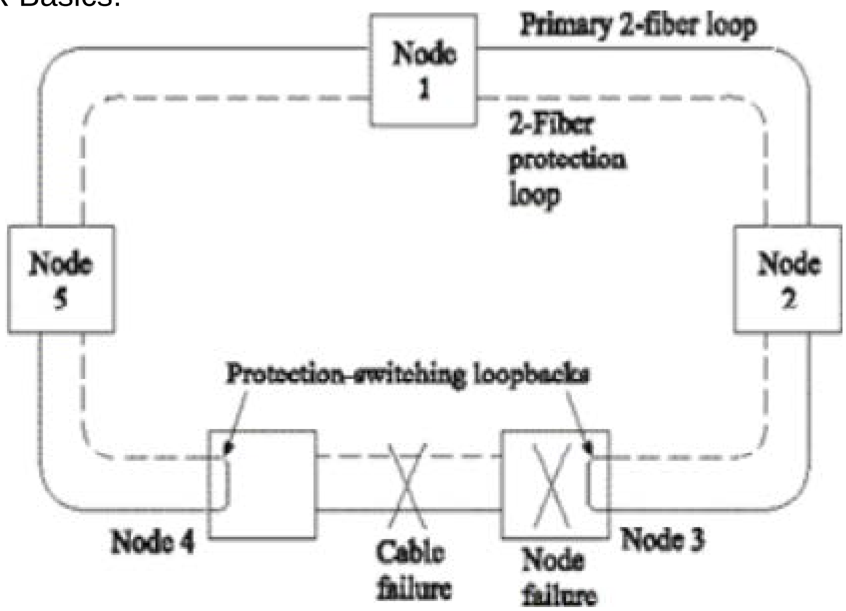
(b)

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.

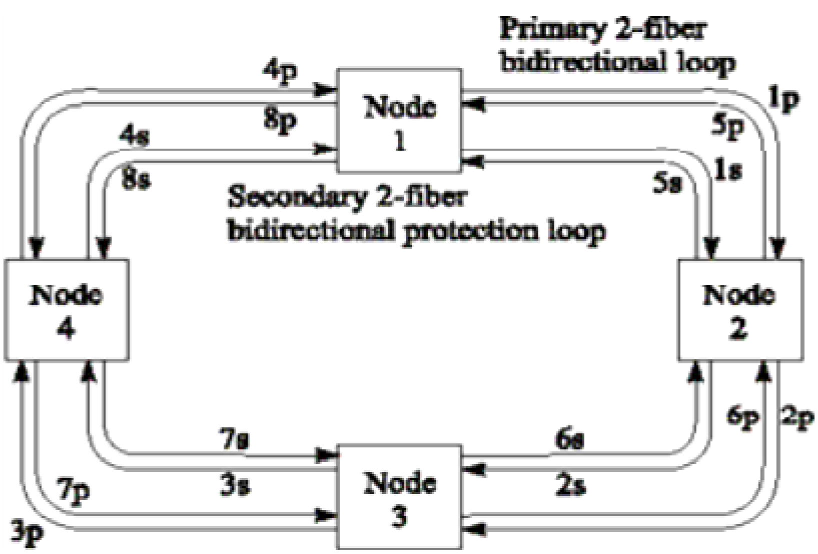


4-Fiber BLSR Basics:



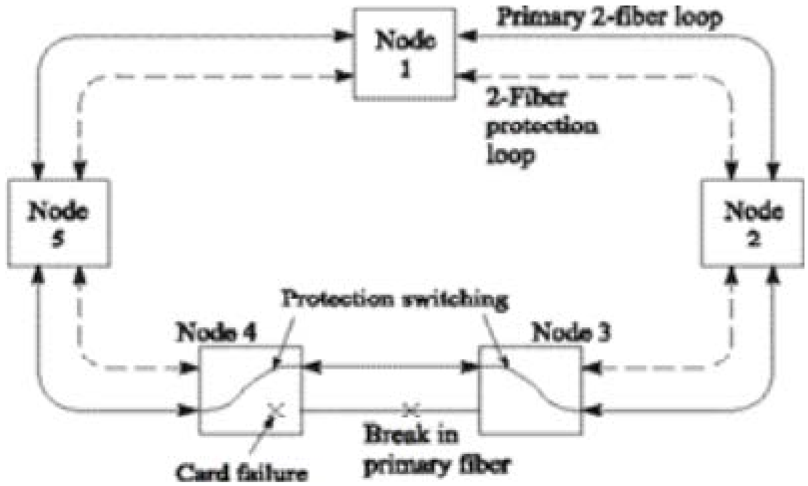
Node 1-3; 1p, 2p   Node 3-1; 3p, 4p

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:



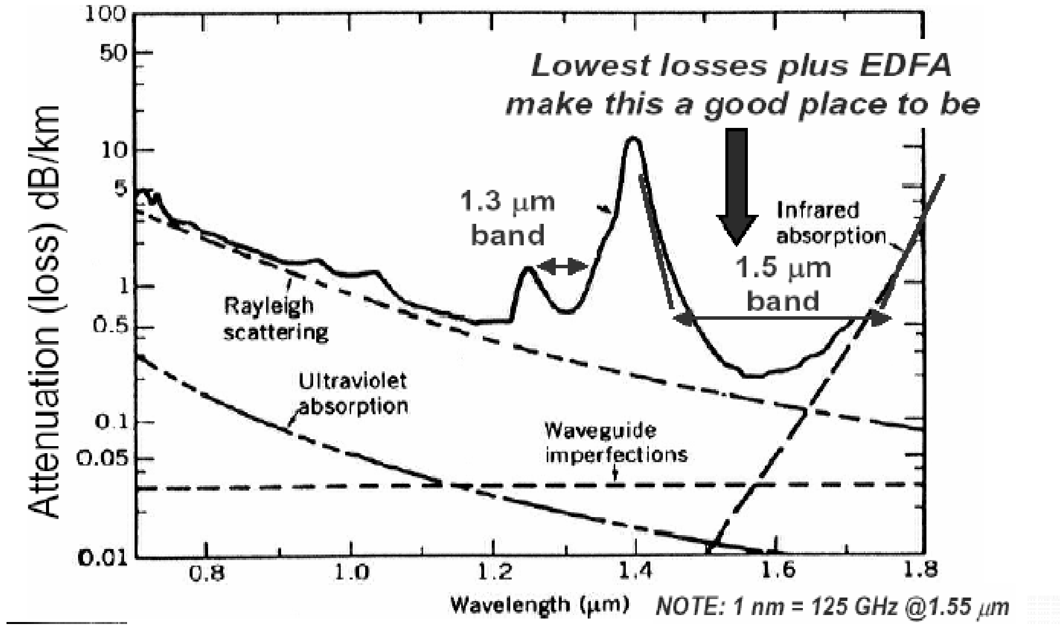
If both primary and secondary are cut, still the connection is not lost, but both the primary and secondary fibers of the entire ring are occupied.

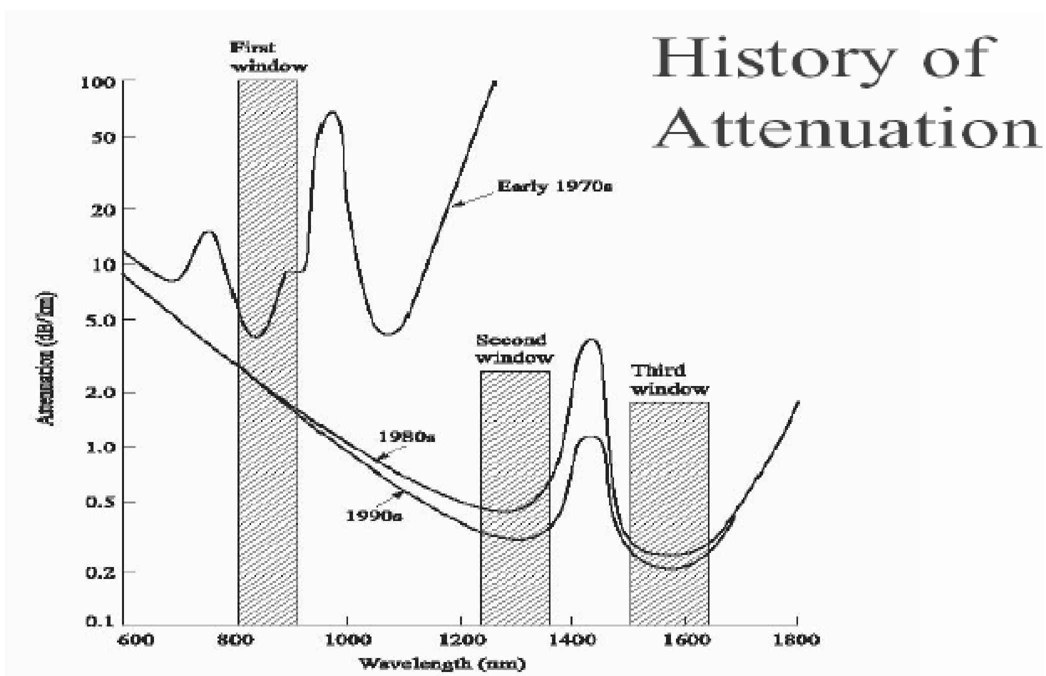
2. Explain in detail about optical CDMA[CO5-L2]

OCDMA combines high BW FO Media with Flexibility of CDMA to provide high-speed connectivity Each user transmits its unique Signature Sequence using shot Optical Pulses to transmit bit1 and all-zero sequence to transmit bit 0

Number of OOCs > Number of Users

Spread Spectrum Communication Patented in 1941 by Hedy Lamar & George Antheil (not Implemented at that time) CDMA considered for Cellular Mobile in the late 70's – Now an Important Tech. and 3G/4G Technology More Recently CDMA has been Explored for FO Communications: OCDMA





Short and Beat Noise:

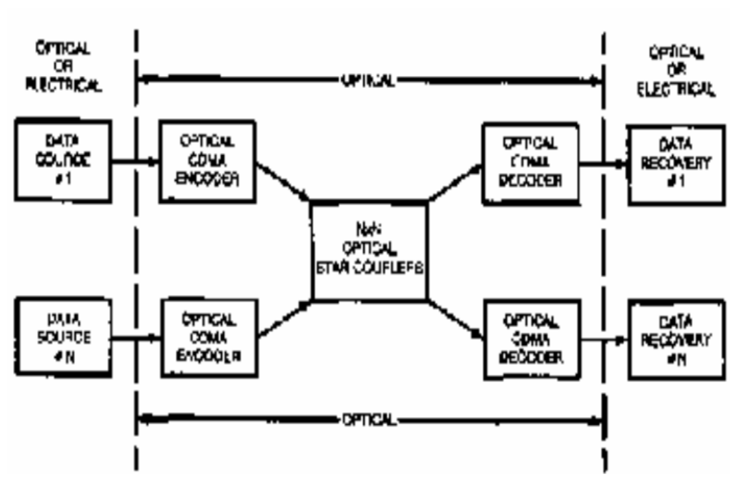
Optical power from other users on same wavelength channels lead to short and beat noise. The short noise increases linearly with increase in number of active users. Limits the scalability of OCDMA systems. Optical beat noise is a dominant source of noise in some OCDMA systems. Optical FEC techniques are proposed to overcome the effect of short noise. Clever control of optical phase coherence can be used to cancel the effect of the beat noise.

Expensive Optical HW is the Biggest Barrier:

The use of tunable FBGs as encoders, both at head-end of an OCDMA system as well as user terminal, make it both expensive and bulky. The use of broad-band light sources such as a BB LED (cheap but low power) or spectrally slicing the amplified spontaneous emission (ASE) of EDFA, or array of laser diodes tuned to different wavelengths. Both EDFAs and Laser Diode Arrays are expensive. Integration is the only solution.

Optical CDMA Components:

Properties of “good” CDMA Code Must be easily distinguishable from a shifted copy of itself Must be easily distinguishable from (a possibly shifted version of) any other code in the sets mall auto/cross correlation Maximal-Length codes have these properties but are bipolar (high =1, low=-1)Not Suitable for Optical Signals which are generally intensity based (high = 1 and low =0) i.e. Uni-polar Available OOCs are very sparse pseudo orthogonal uni-polar having low cross-correlation but not enough to facilitate expected BER of 10-9under MA, thus can have MAI Other Sophisticated OOCs require coherence, thus are expensive and complex



3. Describe ultra high capacity network [CO5-L1]

The global data traffic is continuing to increase driven by the ever-increasing computing powers, memory capacity as well as large user applications, and rapidly-increasing wired/wireless access speeds. As we look back on the last three decades since 80’s, we have enjoyed various great inventions as shown in Fig. 1, achieving a capacity increase of as much as 60 dB from 100 Mb/s up to 100 Tb/s (2dB/year), and we will probably need a similar scalability for the next three decades. Recent experimental and theoretical studies, however, strongly suggest that we are approaching a fundamental capacity limit in single-mode fibers due to fiber nonlinearities, optical amplifier bandwidth, and fiber fuse. Space-division multiplexing (SDM) to utilize the last degree of freedom of “space”, initially proposed more than three decades ago, has revived and has been intensively studied recently as a means to substantially increase the transmission capacity per fiber in a cost-effective and energy-efficient way.

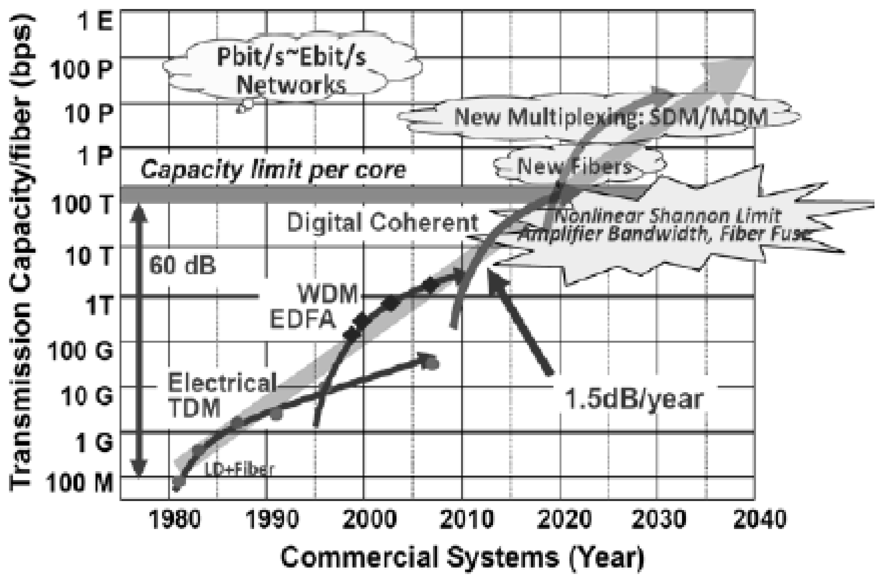


Fig. 1. Evolution of optical transmission technologies.

Recent progress in ultrahigh capacity optical communications technologies based on SDM:

Two SDM schemes based on multi-core fibers (MCFs) [8-10] and multi-mode (few-mode) fibers (MMFs or FMFs) have been proposed. When multiple independent modes are used as an independent channel, the multiplexing scheme is also called mode-division multiplexing (MDM). Recently, few-mode multi-core fibers (FMMCFs) have also been proposed combining the two fibers to further increase the transmission capacity. As shown in Fig. 2, new components for SDM are space-multiplexer (SDM-MUX) to couple light from different cores or different modes into SDM fibers, SDM fibers, SDM optical amplifiers to amplify SDM signals, space-demultiplexer (SDM-DEMUX), optical connectors, mode exciters (generators) in the case of MDM, and MIMO processing.

Major important characteristics of the passive components are low insertion loss, low core/mode dependent loss, low crosstalk among modes/cores and wide bandwidth to support WDM/SDM signals. SDM optical amplifiers are also a challenge where low core/mode/wavelength dependent, wide bandwidth amplification characteristics with high gain and low noise figures (NFs) are desirable in a energy efficient manner. Much progress has been made in MDM transmission, employing well designed FMFs or coupled MCFs either with or without multiple-input multiple output (MIMO) processing, in which a transmission distance up to 4,200 km or 57.6 Tb/s net capacity over 119 km have been reported. MDM experiment based on orbital angular momentum (OAM) modes has also been demonstrated where 400 Gb/s QPSK data was transmitted recently over 1.1 km.

SDM transmission utilizing low crosstalk MCFs has also seen many experimental demonstrations with capacity over 100 Tb/s, 300 Tb/s up to 1 Pb/s, employing uncoupled 7-core, 19-core, and 12-core MCFs , respectively or over 1,000 km. Multi-mode (MM) or multi-core (MC) optical amplifiers are strongly required for long-haul systems and should be major enablers to make SDM systems cost-effective and energy-efficient compared to present systems.

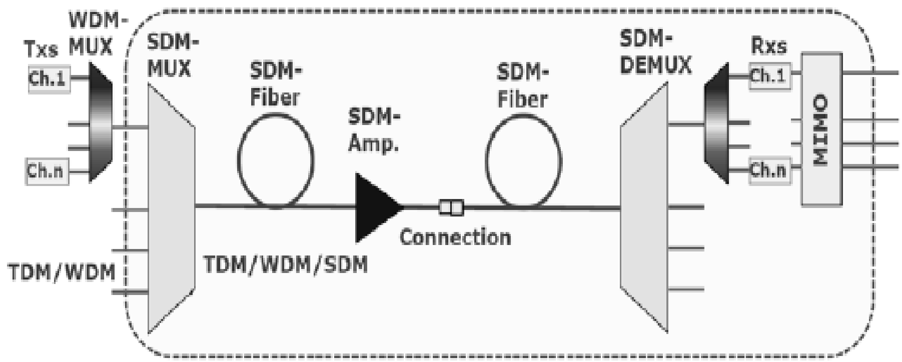


Fig. 2. Basic components of SDM systems.

MM or MC amplifiers, either EDFA-based or Raman-based, have been proposed and used in the transmission experiments. Nonlinearity in these new fibers has also begun to be studied. Recently, one Pb/s transmission (12SDM x 222 WDM x 456 Gb/s) over 52 km with an aggregate spectral efficiency of 91.4 b/s/Hz has been demonstrated employing a low crosstalk, a one-ring structured 12-core MCF and PDM-32 QAM modulation where the MCF has a core pitch of 37 μm, a cladding diameter of 225 μm, and the effective core area (Aeff) at 1550 nm and1625 nm are 80.7 μm2 and 84.7 μm2 on average, respectively. Attenuation at 1550 nm and 1625 nm are 0.199dB/km and 0.207 dB/km, respectively.

4. Explain detail about wavelength routing optical networks[CO5-L1]

This is an optical network that consists of OXCs interconnected by WDM fibers, with each fiber consisting of W wavelengths

It switches optically all the incoming wavelengths of the input fibers to the outgoing wavelengths of the output fibers.

For instance, it can switch the optical signal on incoming wavelength λi of input fiber k to the outgoing wavelength λi of output fiber m.

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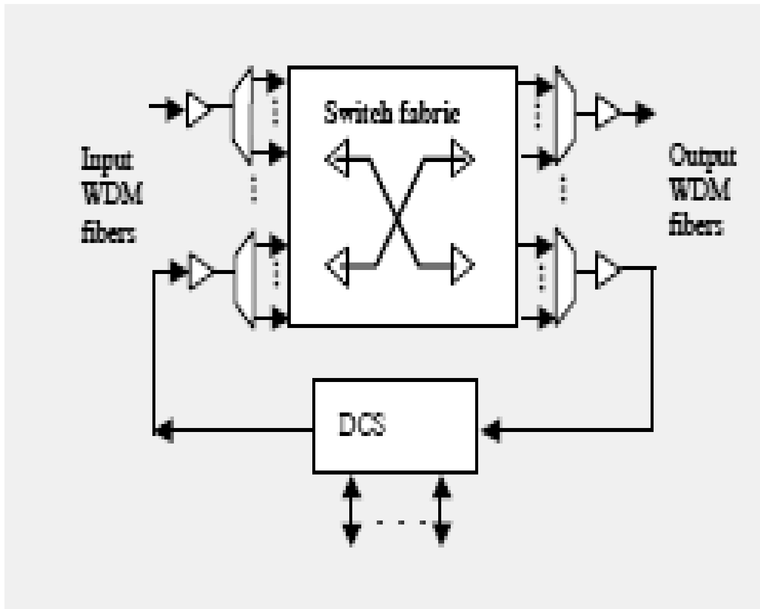


Converters:

If it is equipped with converters, it can also switch the optical signal of the incoming wavelength λi of input fiber k to another outgoing wavelength λj of the output fiber m. This happens when the wavelength λi of the output fiber m is in use.

Optical add/drop multiplexer (OADM):

An OXC can also be used as an OADM. That is, it can terminate the optical signal of a number of incoming wavelengths and insert new optical signals on the same wavelengths in an output port. The remaining incoming wavelengths are switched through as described above.

Transparent switch:

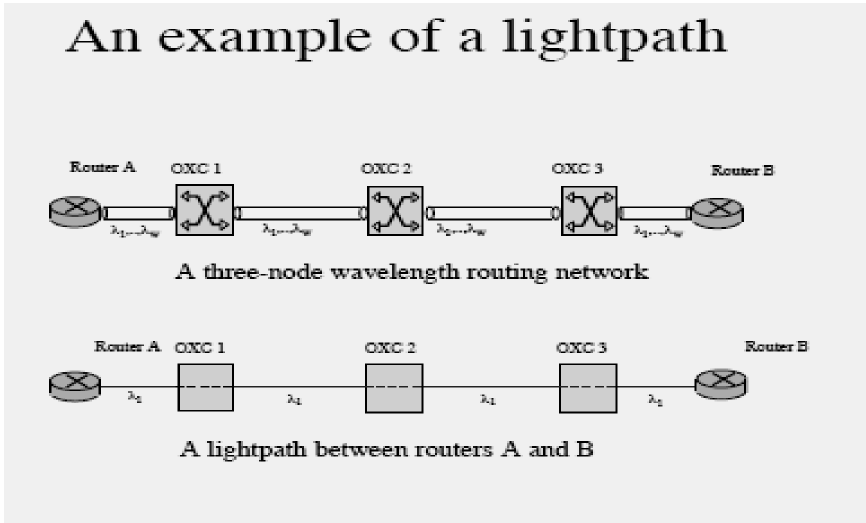
The incoming wavelengths are switched to the output fibers optically, without having to convert them to the electrical domain.

Opaque switch:

The input optical signals are converted to electrical signals, from where the packets are extracted. Packets are switched using a packet switch, and then they are transmitted out of the switch in the optical domain.

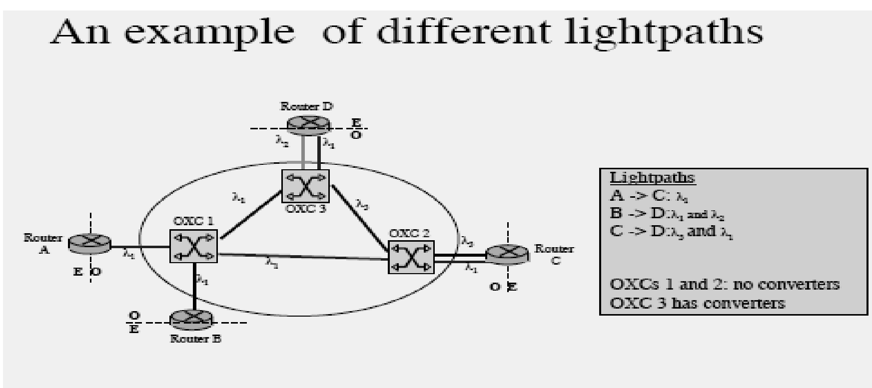
Lightpaths:

• Wavelength routing networks are circuits witched networks.
• In order for a user to send data to another user, a connection has to be first setup.
•This connection is a circuit-switched connection and it is established by allocating a wavelength on each hop along the connection's path



When establishing a lightpath over a wavelength routing network, the same wavelength has to be used on every hop along the path. If the required wavelength is not available at the outgoing fiber of an OXC through which the light path has to be routed, then the establishment of the light path is blocked, and a notification message is sent back to the user.

In order to decrease the probability that a light path is blocked, the OXC can be equipped with converters. A converter can transform the optical signal transmitted over a wavelength to another wavelength.



In an OXC, for each output fiber with W wavelengths, there may be c converters, where $0 \leq c \leq W$.

No conversion: $c=0$

Partial conversion: $0 < c < W$

Full conversion: $c=W$

A converter can only transform a signal on a wavelength λ to another wavelength which is within a few nm from wavelength λ.