SRI MUTHUKUMARAN INSTITUTE OF TECHNOLOGY

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DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

YEAR/SEM: IV/VII
SUBJECT CODE & NAME: EC 8751- OPTICAL COMMUNICATION

TWO MARKS QUESTIONS AND ANSWERS

UNIT II- Transmission Characteristics of Optical Fibers

1. **Differentiate linear scattering from non-linear scattering.**
   Linear scattering mechanisms cause the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly into a different mode. Non-linear scattering causes the optical power from one mode to be transferred in either the forward or backward direction to the same or other modes at different frequencies.

2. **What is meant by Fresnel reflection?**
   When the two joined fiber ends are smooth and perpendicular to the axes, and the two fiber axes are perfectly aligned, the small proportion of the light may be reflected back into the transmitting fiber causing attenuation at joint. This is known as Fresnel reflection.

3. **What are the types of material absorption losses in silica glass fibers?**
   The types of material absorption losses in the glass composition are
   - Absorption by impurity atoms in the glass material.
   - Intrinsic absorption by the basic constituent atoms in the glass material.

4. **How do we minimize optical losses at the interface?**
   Optical losses at the interface can be minimized if
   - Jointed fiber ends are smooth
   - Perpendicular to fiber axis
   - Two fiber axes are perfectly aligned

5. **What is meant by attenuation coefficient of a fiber?**
   If P(0) is the optical power in a fiber at the origin (at Z = 0), then the power P(Z) at a distance z further down the fiber is
   $P(z) = P(0)\, e^{-\alpha_p z}$
   The above equation can be rewritten as
   $\alpha_p = (1 / z)\ \{ P(0) / P(z)\}$. Where α_p is the fiber attenuation coefficient given in units of km^{-1}
6. **What is intrinsic absorption in optical fibers?**
   The absorption caused by the interaction with one or more of the major components of the glass is known as intrinsic absorption.
7. **What are the factors that cause Rayleigh scattering in optical fibers?**
   The inhomogeneity's of a random nature occurring on a small scale compared with the wavelength of the light in optical fiber causes Rayleigh scattering.
8. **What is meant by dispersion in optical fiber?**
   Dispersion of the transmitted optical signal causes distortion in both analog and digital signals along optical fibers. Dispersion mechanisms within the fiber cause broadening of the

transmitted light pulses as they travel along the channel.

9. **What are the ways to reduce macrobending losses?**

Ways to reduce macrobending losses are

- Designing fibers with large relative refractive index differences.
- Operating at the shortest wavelength possible.

10. **What are the factors that cause Mie scattering in optical fibers?**

The nonperfect cylindrical structure of the waveguide by the fiber imperfections causes Mie scattering in optical fibers.

11. **Define – Group Velocity Dispersion (GVD) .**

Intra-modal dispersion is pulse spreading that occurs within a single mode. The spreading arises from the finite spectral emission width of an optical source. This phenomenon is known as Group Velocity Dispersion.

12. **What is meant by linear scattering?**

Linear scattering mechanisms cause the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly into a different mode.

13. **Define- Beat Length**

Beat Length is defined as the period of interference effects in a bi-refringent medium. When two waves with different linear polarization states propagate in a bi-refringent medium, their phases will evolve differently.

14. **What is intra Modal dispersion?**

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.

15. **Why intra modal dispersion occurs?**

Intra modal dispersion occurs because colours of light travel through different materials and different waveguide structures at different speeds.

16. **What are the causes of intra modal dispersion?**

There are two main causes of intra modal dispersion.

They are

- Material Dispersion
- Waveguide Dispersion.

17. **What is wave guide dispersion?**

Wave guide dispersion occurs because of a single mode fiber confines only about 80% of optical power to the core. Dispersion 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.

18. Compare splices and connectors.

Splices	Connectors
Permanent or semipermanent joints	Temporary joints
Splice loss is low	Connector loss is high

19. Define - Cross Talk in couplers

Cross talk is a measure of isolation between two input or two output ports. It is an important Disturbance in any form of communication that needed to be reduced.

20. Define- Polarization Maintaining Fiber? (PMF)

PMF is an optical fiber in which the polarization of linearly polarized light waves launched into the fiber is maintained during propagation, with less or no cross coupling of optical power between the polarizations modes. Such fiber is used in special application where processing the polarization is essential.

21. What is material dispersion?

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 mode wave guide.

22. What is group velocity?

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

$$V_g = C^* (d \beta / dk)$$

23. What is polarization?

Polarization 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.

24. What is pulse broadening?

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 neighbouring pulses. After a time ‘t’, the adjacent pulses can no longer be individually distinguished at the receiver and error will occur.

25. What is profile dispersion?

A fiber with a given index profile (alpha) will exhibit different pulse spreading according to the source wavelength used. This is called profile dispersion.

26. What is polarization mode dispersion (PMD)?

The difference in propagation times between the two orthogonal polarization modes will result pulse spreading. This is called as polarization mode dispersion. (PMD)

27. Define – Dispersion Flattening

The reduction of fiber dispersion by spreading the dispersion minimum out over a wide range.This approach is known as dispersion flattening.

28. What is fiber birefringence?

Imperfections in the fiber are common such as symmetrical 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.

29. What is mode coupling?

Mode coupling 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 diameter etc.

30. Define- Dispersion Shifted Fiber

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 and material dispersion can then be shifted to zero dispersion point to long wavelength. The resulting optical fiber are called as dispersion Shifted Fiber.

31. What is M-C fiber?

Fibers that have a uniform refractive index throughout the cladding is called as M-C fiber or Matched cladding fiber.

32. Define - Cut-off Wavelength of the fiber

The cut-off wavelength is defined as the minimum value of wavelength that can be transmitted through the fiber. The wavelengths greater than the cut-off wavelength can be transmitted.

33. Write a note on scattering losses.

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.

34. What is intramodal delay?

The factor which gives rise to pulse spreading is called as intra-modal delay. It is a result of each mode having a different value of group velocity at a single frequency.

35. Mention the losses responsible for attenuation in optical fibers.

The losses which are responsible for attenuation in optical fibers are as follows

- Absorption losses
- Scattering losses
- Bending losses

36. What is the function of coupler? What are the different types of optical couplers?

A coupler is a device which is used to combine and split signals in an optical network..
Different types of couplers are

- Directional coupler
- Star coupler
- Fused fiber coupler
- 2 x 2 coupler

37. What are the requirements of good couplers?

The requirements of good couplers are

- Good optical couplers should have low insertion losses.
- Insensitive to temperature
- Good optical couplers should have low polarization-dependent loss.
- Reliability

38. What is intermodal dispersion?

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 as group velocity dispersion or intermodal dispersion.

39. Write the light ray guiding condition.

Light ray that satisfies total internal reflection at the interface of the higher refractive index core andThe lower refractive index cladding can be guided along an optical fiber.

40. What do you mean by Extrinsic absorption?

Absorption phenomena due to impurity atoms present in the fiber is called as Extrinsic absorption.

41. What is the measure of information capacity in optical waveguide?

It is usually specified by bandwidth distance product in Hz. For a step index fiber the various distortion effects tend to limit the bandwidth distance product to 20 MHz.

42. Define - Microscopic Bending

Fiber losses occur due to small bending arise while the fiber is inserted into a cable is known as Microscopic Bending.

43. Write Short notes on Scattering losses.

Scattering losses caused by the interaction of light with density fluctuations within a fiber. Density changes are produced when optical fibers are manufactured. During manufacturing, regions of higher and lower molecular density areas, relative to the average density of the fiber, are created. Light traveling through the fiber interacts with the density areas light is then partially scattered in all directions.

44. What is Rayleigh scattering?

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.

45. Write the expression for Rayleigh Scattering Loss. The

expression for Rayleigh Scattering loss is given by $\alpha_{scat} = (8\pi^3/3\lambda^2)$

$(n^2 - 1)^2 k_B T_f \beta_T$

where n= refractive index k_B =

Boltzman constant T_f = fictive

temperature

β_T = isothermal compressibility

λ = operative wavelength

46. When will Rayleigh Scattering Occurs?

Rayleigh scattering is the main loss mechanism between the ultraviolet and infrared regions. Rayleigh scattering occurs when the size of the density fluctuation (fiber defect) is less than one-tenth of the operating wavelength of light.

47. What are the uses of fiber optical connectors?

Optical fiber connectors are used to join optical fibers where a connect/disconnect capability is required.

48. What do you mean by fiber optic coupler?

A **fiber optic coupler** is a device used in optical fiber systems with one or more input fibers and one or several output fibers. Light entering an input fiber can appear at one or more outputs and its power distribution potentially depending on the wavelength and polarization.

49. What do you mean by fiber optic connectors?

An optical fiber connector terminates the end of an optical fiber, and enables quicker connection and disconnection than splicing. The connectors mechanically couple and align the cores of fibers so light can pass. Better connectors lose very little light due to reflection or misalignment of the fibers. In all, about 100 fiber optic connectors have been introduced to the market.

50. List the features of optical connectors. The

features of good connector are:

- Low insertion loss
- Low cost and low environmental sensitivity
- Reliability
- High return loss (*low* amounts of reflection at the interface)
- Ease of use
- Ease of installation

51. What is the need for fiber alignment?

Fiber optic sensors constitute the core of telecommunication markets as well as being important part of automotive and industrial applications. With the recent renewed growth and technology advances in fiber optics, there is an increasing need for automating photonics alignment.

52. What do you mean by micro-bend Losses?

Microbends are small microscopic bends of the fiber axis that occur mainly when a fiber is cabled.Microbend losses are caused by small discontinuities or imperfections in the fiber. Uneven coating applications and improper cabling procedures increase micro-bend loss. External forces are also a source of micro- bends.

53. What do you mean by macro-bend losses?

Macrobend losses are observed when a fiber bend's radius of curvature is large compared to the fiber diameter. Light propagating at the inner side of the bend travels a shorter distance than that on the outer side.

54. List the two major categories of fiber joints.

The two major categories of fiber joints are

- Fiber splices
- Fiber connectors

55. What are connectors? What are the types of connectors?

The connectors are used to join the optical sources as well as detectors to the optical fiber temporarily. They are also used to join two optical fibers. The two major types of connectors are

- Lensed type expanded beam connector
- Ferrule type connector.

56. What are splices?

The splices are generally permanent fiber joints, whereas connectors are temporary fiber joints. Splicing is a sort of soldering.

57. What are the requirements of splices?

The requirements of splices are

- Should be easy to install
- Should have minimum power loss
- Should be strong and light in weight
- Should cause low attenuation.

58. What are the methods of fiber splicing?

There are three methods of fiber splicing. They are :

- Electric arc fusion splicing or fusion splicing
- Mechanical splicing
- V-groove splicing or loose tube splicing.

PART – B

1. Clearly bring out the differences between intra and intermodal dispersion.

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

1. Material dispersion :

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

2. Waveguide dispersion :

The waveguiding of the fiber may also create chromatic dispersion. This results from the variation in group velocity with wavelength for a particular mode. Considering the ray theory approach, it is equivalent to the angle between the ray and the fiber axis varying with wavelength which subsequently leads to a variation in the transmission times forthe rays, and hence dispersion. For a single mode whose propagation constant is β, the fiber exhibits waveguide dispersion when $d^2\beta/d\lambda^2 \neq 0$. Multimode fibers, where the majority of modes propagate far from cutoff, are almost free of waveguide dispersion and it is generally negligible compared with material dispersion (≈0.1 to 0.2 ns/ km).However, with single-mode fibers where the effects of the different dispersion mechanisms are not easy to separate, waveguide dispersion may be significant.

Intermodal dispersion :

Pulse broadening due to intermodal dispersion (sometimes referred to simply as modal or mode dispersion) results from the propagation delay differences between modes within a multimode fiber. As the different modes which constitute a pulse in a multimode fiber travel along the channel at different group velocities, the pulse width at the output is dependent upon the transmission times of the slowest and fastest modes. This dispersion mechanism creates the fundamental difference in the overall dispersion for the three types of fiber.

Thus multimode step index fibers exhibit a large amount of intermodal dispersion which gives the greatest pulse broadening.

However, intermodal dispersion in multimode fibers may be reduced by adoption of an optimum refractive index profile which is provided by the near-parabolic profile of most graded index fibers.

Hence, the overall pulse broadening in multimode graded index fibers is far less than that obtained in multimode step index fibers (typically by a factor of100). Thus graded index fibers used with a multimode source give a tremendous bandwidth advantage over multimode step index fibers. Under purely single-mode operation there is no intermodal dispersion and therefore pulse broadening is solely due to the intramodal dispersion mechanisms. In theory, this is the case with single-mode step index fibers where only a single mode is allowed to propagate. Hence they exhibit the least pulse broadening and have the greatest possible bandwidths, but in general are only usefully operated with single-mode sources.

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

2. **Compare linear and non-linear scattering losses in optical fibers.**

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

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

1.Rayleigh scattering :

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

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

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

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F \quad (2.4)$$

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

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.

$$\mathcal{L} = \exp(-\gamma_R L) \quad (2.5)$$

2.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

b) Nonlinear scattering losses :

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

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

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

1. **Stimulated Brillouin Scattering :**

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

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

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

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

2. **Stimulated Raman scattering :**

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

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

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

3. Explain the various types of dispersion mechanisms and factors contributing to signal distortion.

Dispersion :

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

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

Hence:

$$B_T \le \frac{1}{2\tau} \qquad (2.10)$$

The conversion of bit rate to bandwidth in hertz depends on the digital coding format used. For metallic conductors when a nonreturn-to-zero code is employed, the binary 1 level is held for the whole bit period τ. In this case there are two bit periods in one

wavelength (i.e. 2 bits per second per hertz), as illustrated in Figure 2.8(a). Hence the maximum bandwidth *B* is one-half the maximum data rate or:

$$B_T(\max) = 2B \qquad (2.12)$$

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

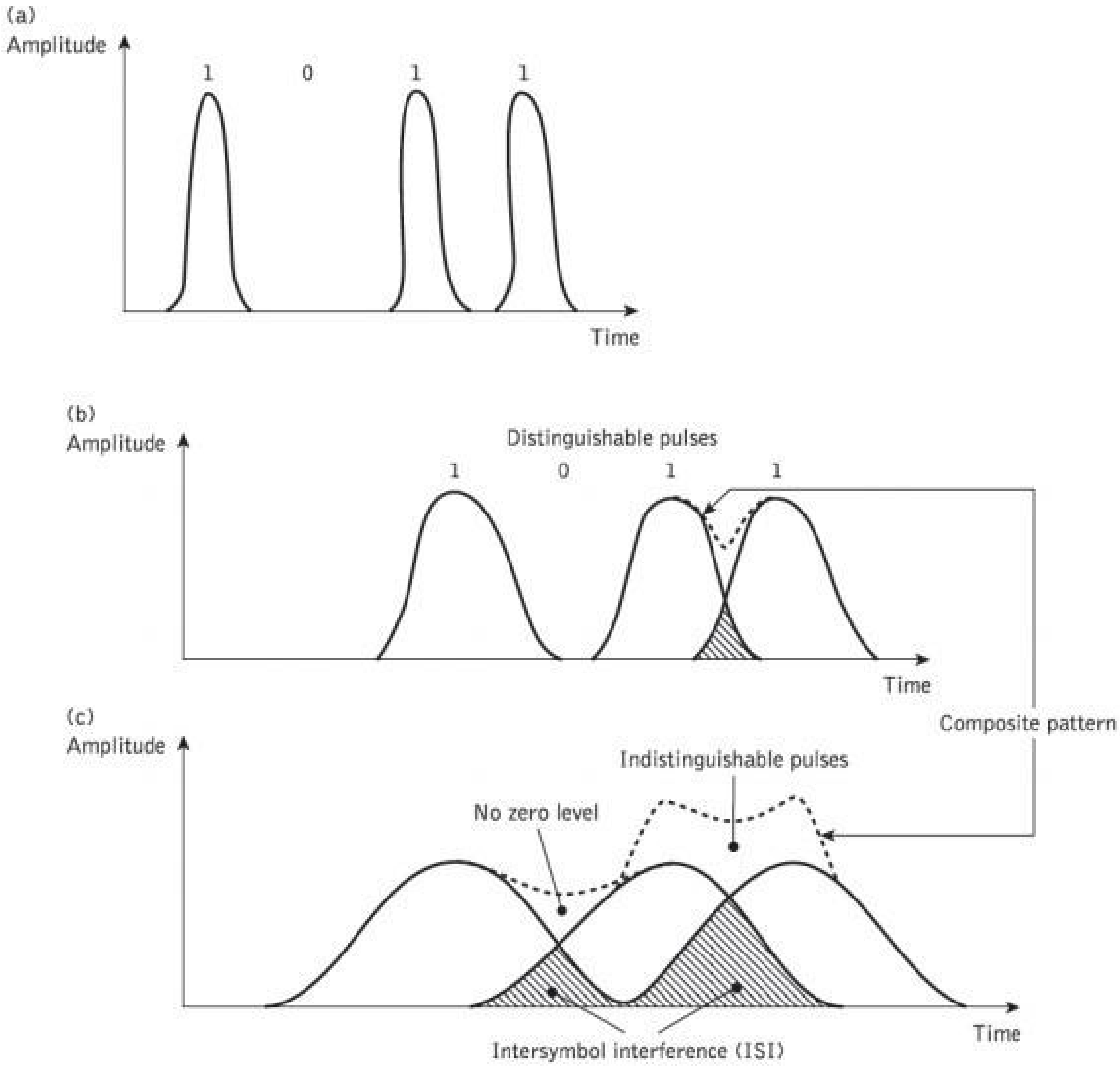


Figure 2.7 An illustration using the digital bit pattern 1011 of the broadening of light pulses as they are transmitted along a fiber: (a) fiber input; (b) fiber output at a distance $L1$; (c) fiber output at a distance $L2 > L1$

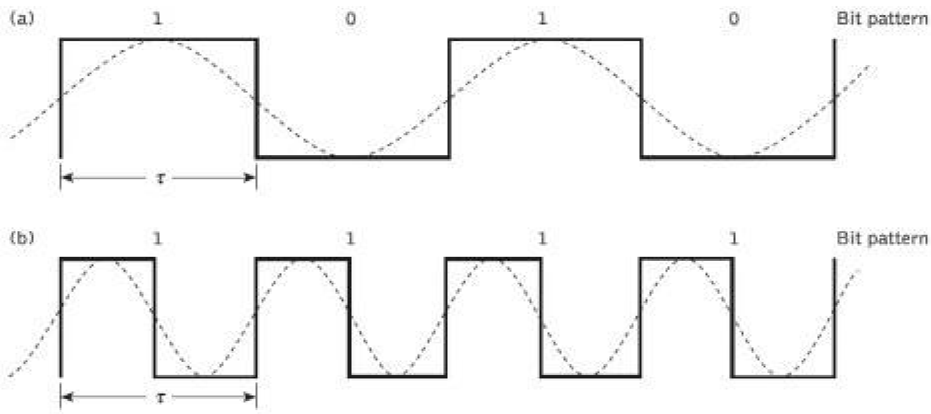


Figure 2.8 Schematic illustration of the relationships of the bit rate to wavelength for digital codes: (a) nonreturn-to-zero (NRZ); (b) return-to-zero (RZ)

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

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

a)Intramodal Dispersion :

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

1.Material dispersion :

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

Hence the group delay is given by:

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

Where *n*1 is the refractive index of the core material. The pulse delay 🔀m due to material

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

dispersion in a fiber of length *L* is therefore:
For a source with rms spectral width and a mean wavelength, the rms pulse broadening due to material dispersion 📅m may be obtained from the expansion of Eq. (2.14) in a

Taylor series about where:

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

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

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

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

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

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

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

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

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

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

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

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

2.Waveguide dispersion :

The waveguiding of the fiber may also create chromatic dispersion. This results from the variation in group velocity with wavelength for a particular mode. Considering the ray theory approach, it is equivalent to the angle between the ray and the fiber axis varying with wavelength which subsequently leads to a variation in the transmission times for the rays, and hence dispersion. For a single mode whose propagation constant is β, the fiber exhibits waveguide dispersion when $d2\beta/d\omega 2 != 0$. Multimode fibers, where the majority of modes propagate far from cutoff, are almost free of waveguide dispersion and it is generally negligible compared with material dispersion (≈0.1 to 0.2 ns/ km).

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

b) Intermodal dispersion :

Pulse broadening due to intermodal dispersion (sometimes referred to simply as modal or mode dispersion) results from the propagation delay differences between modes within a multimode fiber. As the different modes which constitute a pulse in a multimode fiber travel along the channel at different group velocities, the pulse width at the output is dependent upon the transmission times of the slowest and fastest modes.

This dispersion mechanism creates the fundamental difference in the overall dispersion for the three types of fiber. Thus multimode step index fibers exhibit a large amount of intermodal dispersion which gives the greatest pulse broadening. However, intermodal dispersion in multimode fibers may be reduced by adoption of an optimum refractive index profile which is provided by the near-parabolic profile of most graded index fibers.

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

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

4. Explain fiber alignment and joint losses in detail.

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

$$r = \left(\frac{n_1 - n}{n_1 + n}\right)^2 \qquad (2.59)$$

transmitting fiber causing attenuation at the joint. This phenomenon, known as Fresnel reflection, is associated with the step changes in refractive index at the jointed interface (i.e. glass–air–glass). The magnitude of this partial reflection of the light transmitted through the interface may be estimated using the classical Fresnel formula for light of normal incidence and is given by where r is the fraction of the light reflected at a single interface, n1 is the refractive index of the fiber core and n is the refractive index of the medium between the two jointed fibers (i.e. for air n =1). However, in order to determine the amount of light reflected at a fiber joint, Fresnel reflection at both fiber interfaces must be taken into account. The loss in decibels due to Fresnel reflection at a single interface is given by:

Hence, using the relationships given in Eqs (2.59) and (2.60) it is possible to determine the optical attenuation due to Fresnel reflection at a fiber–fiber joint.

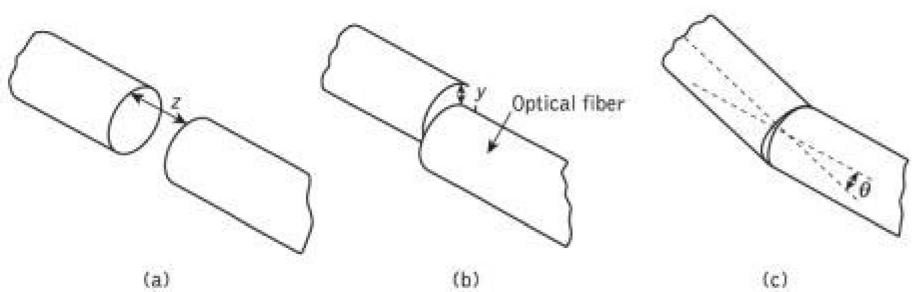


Figure 2.17 The three possible types of misalignment which may occur when jointing compatible optical fibers: (a) longitudinal misalignment; (b) lateral misalignment; (c) angular misalignment

It is apparent that Fresnel reflection may give a significant loss at a fiber joint even when all other aspects of the connection are ideal. However, the effect of Fresnel reflection at a fiber–fiber connection can be reduced to a very low level through the use of an index- matching fluid in the gap between the jointed fibers. When the index-matching fluid has the same refractive index as the fiber core, losses due to Fresnel reflection are in theory eradicated. Unfortunately, Fresnel reflection is only one possible source of optical loss at a fiber joint. A potentially greater source of loss at a fiber–fiber connection is caused by misalignment of the two jointed fibers. In order to appreciate the development and relative success of various connection techniques it is useful to discuss fiber alignment in greater detail.Any deviations in the geometrical and optical parameters of the two optical fibers which are jointed will affect the optical attenuation (insertion loss) through the connection. It is not possible within any particular connection technique to allow for all these variations.

Hence, there are inherent connection problems when jointing fibers with, for instance

✓ different core and/or cladding diameters;

✓ different numerical apertures and/or relative refractive index differences;

✓ different refractive index profiles;

✓ fiber faults (core ellipticity, core concentricity, etc.).

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

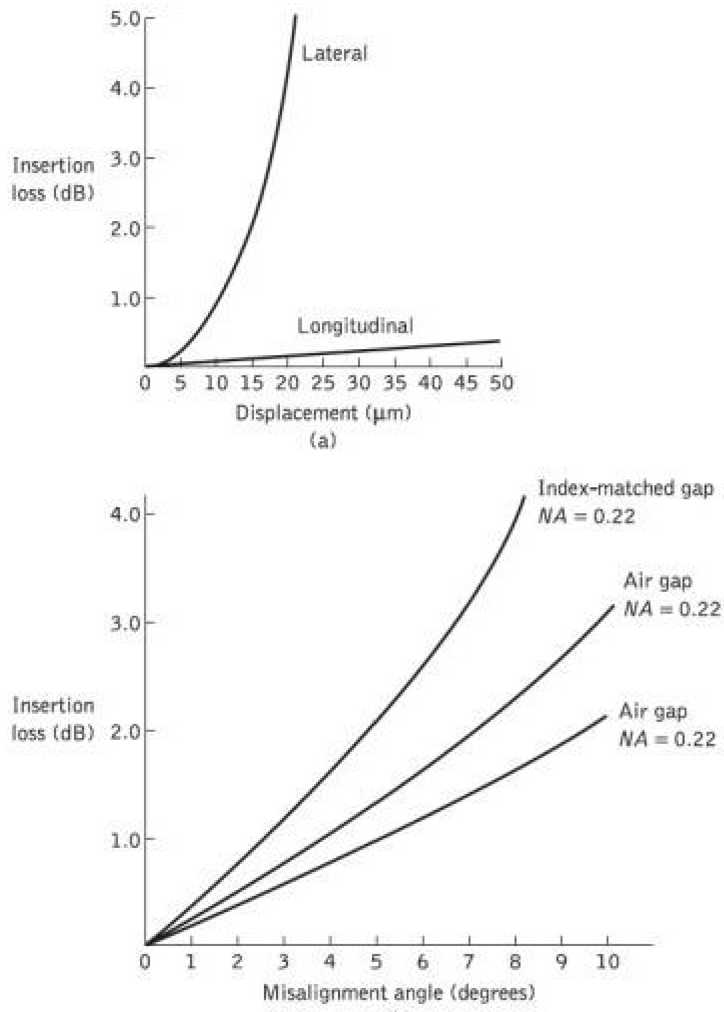


Figure 2.18 Insertion loss characteristics for jointed optical fibers with various types of misalignment: (a) insertion loss due to lateral and longitudinal misalignment for a graded index fiber of 50 μm core diameter.

In this case there is still the problem of the quality of the fiber alignment provided by the jointing mechanism. Examples of possible misalignment between coupled compatible optical fibers are illustrated in Figure 2.17. It is apparent that misalignment may occur in three dimensions: the separation between the fibers (longitudinal misalignment), the offset perpendicular to the fiber core axes (lateral/radial/ axial misalignment) and the angle between the core axes (angular misalignment).

Optical losses resulting from these three types of misalignment depend upon the fiber type, core diameter and the distribution of the optical power between the propagating modes. Examples of the measured optical losses due to the various types of misalignment are shown in Figure 2.18. Figure 2.18(a) shows the attenuation characteristic for both longitudinal and lateral misalignment of a graded index fiber of 50 μm core diameter.

It may be observed that the lateral misalignment gives significantly greater losses per unit displacement than the longitudinal misalignment. For instance, in this case a lateral displacement of 10 μm gives about 1 dB insertion loss whereas a similar longitudinal displacement gives an insertion loss of around 0.1 dB. Figure 2.18(b) shows the attenuation characteristic for the angular misalignment of two multimode step index fibers with numerical apertures of 0.22 and 0.3. An insertion loss of around 1 dB is obtained with angular misalignment of 4° and 5° for the NA =0.22 and NA=0.3 fibers respectively.

It may also be observed in Figure 2.18(b) that the effect of an index-matching fluid in the fiber gap causes increased losses with angular misalignment. Therefore, it is clear that relatively small levels of lateral and/or angular misalignment can cause significant attenuation at a fiber joint. This is especially the case for fibers of small core diameter (less than 150 μm) which are currently employed for most telecommunication purposes.

5. Explain the various fiber splicing techniques in detail .

Fiber splices :

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

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

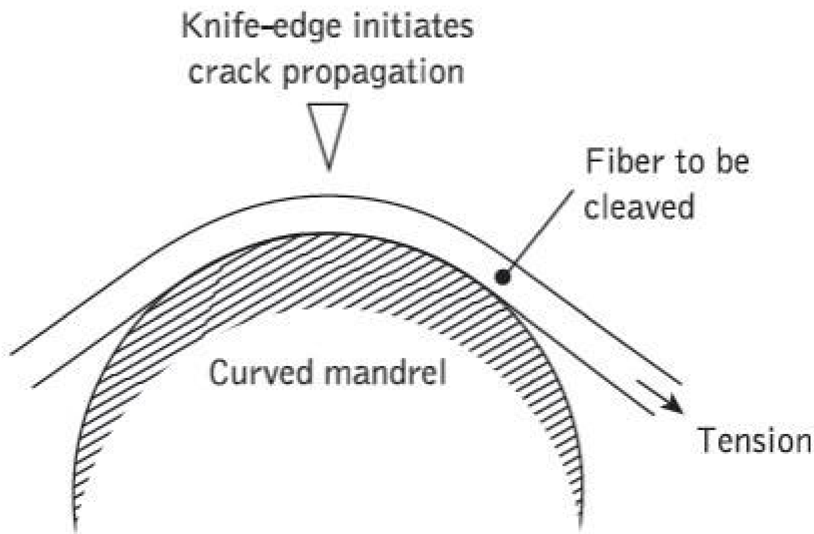


Figure 2.20 Optical fiber end preparation: the principle of scribe and break cutting

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.

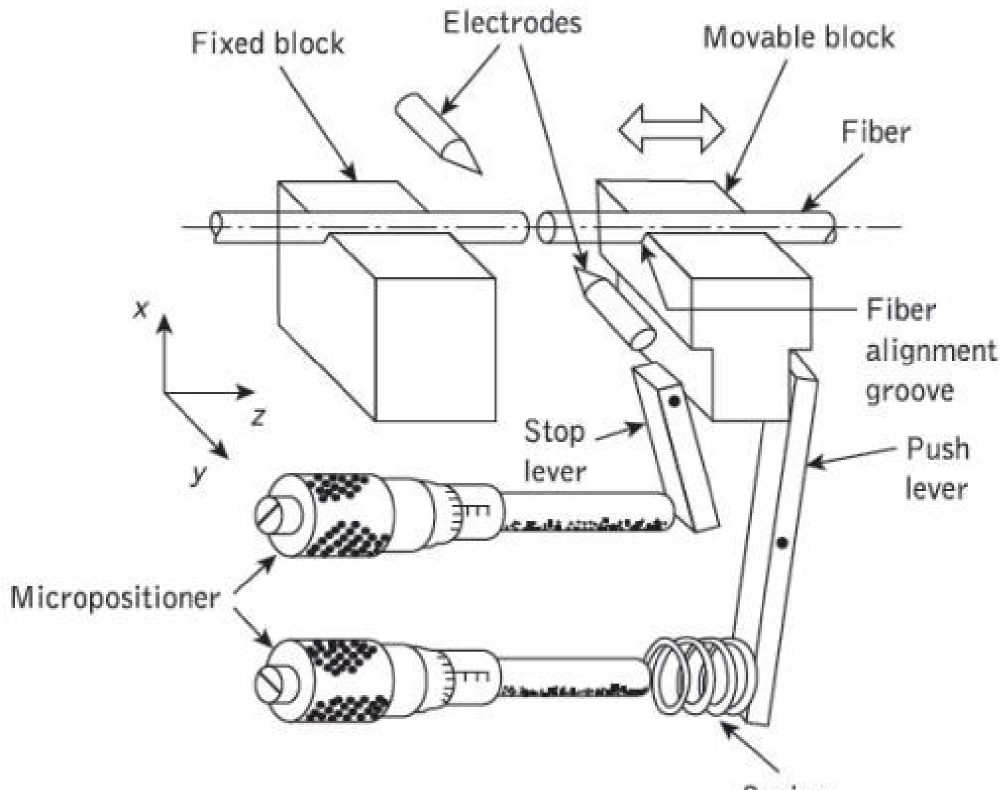
1. Fusion splices

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 oxhydricmicroburners (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.



(a)

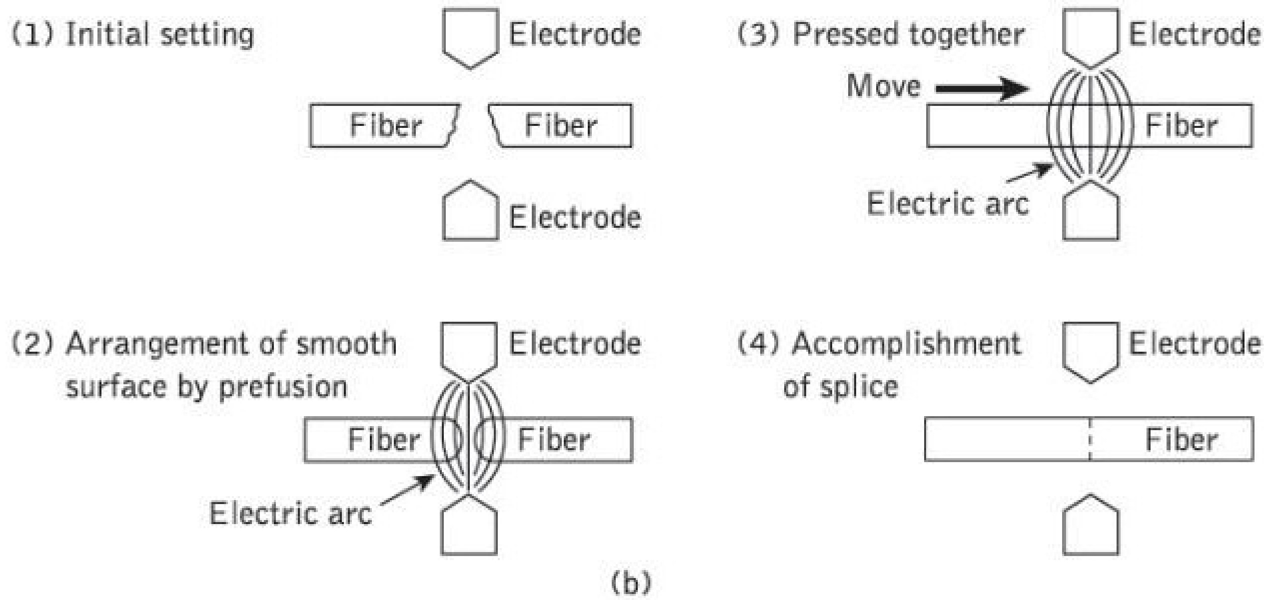


Figure 2.21 Electric arc fusion splicing: (a) an example of fusion splicing apparatus; (b) schematic illustration of the prefusion method for accurately splicing optical fibers

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.

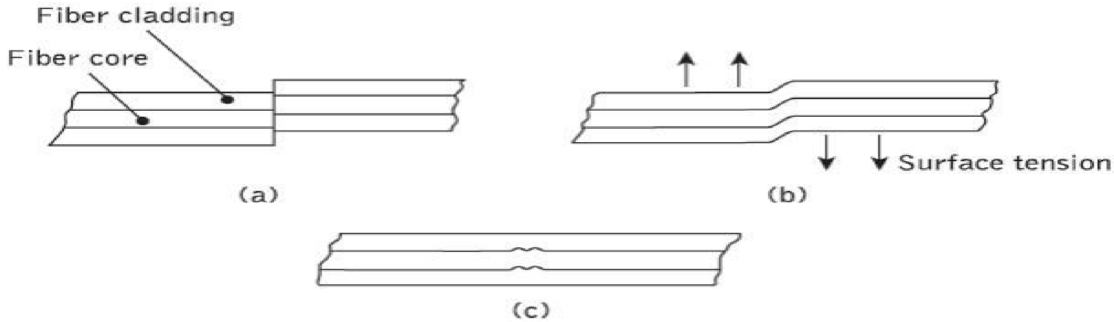


Figure 2.22 Self-alignment phenomenon which takes place during fusion splicing: (a) before fusion; (b) during fusion; (c) after fusion

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.

2. 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.

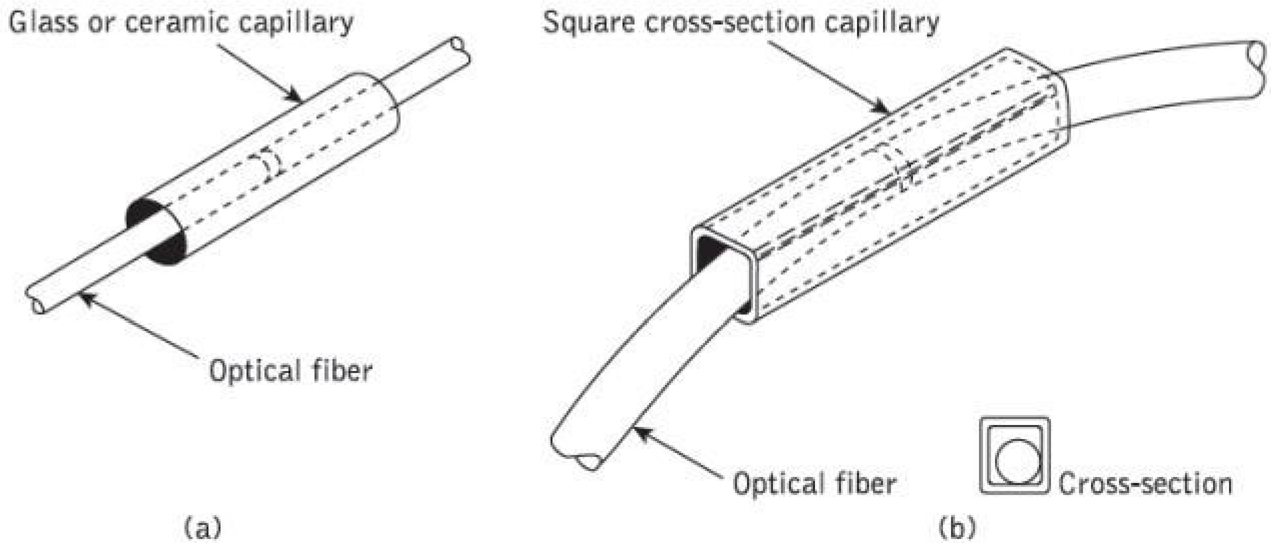


Figure 2.23 Techniques for tube splicing of optical fibers: (a) snug tube splice; (b) loose tube splice utilizing square cross-section capillary

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.

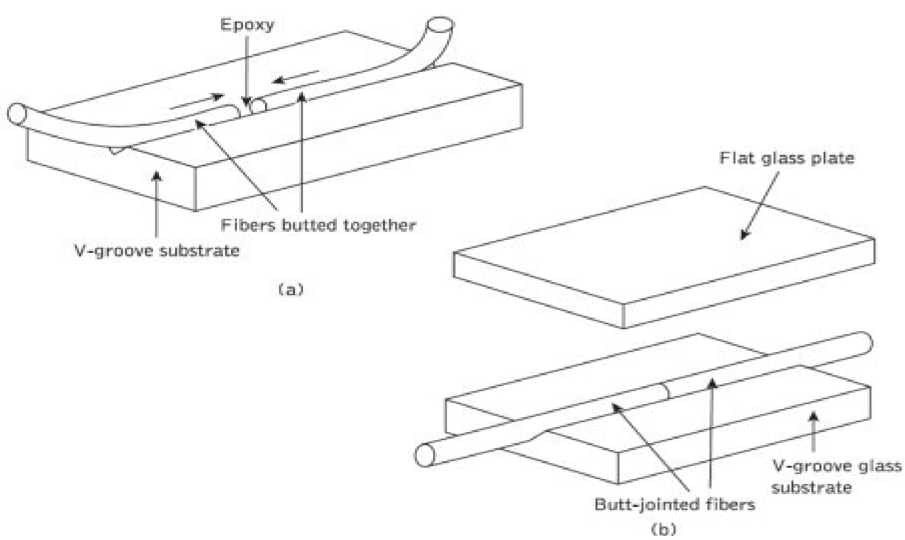


Figure 2.24 V-groove splices

dB

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.

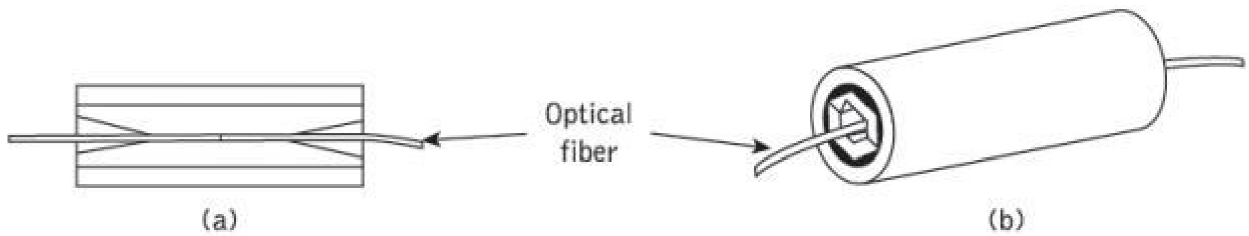


Figure 2.25 The elastomeric splice: (a) cross-section; (b) assembly

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.

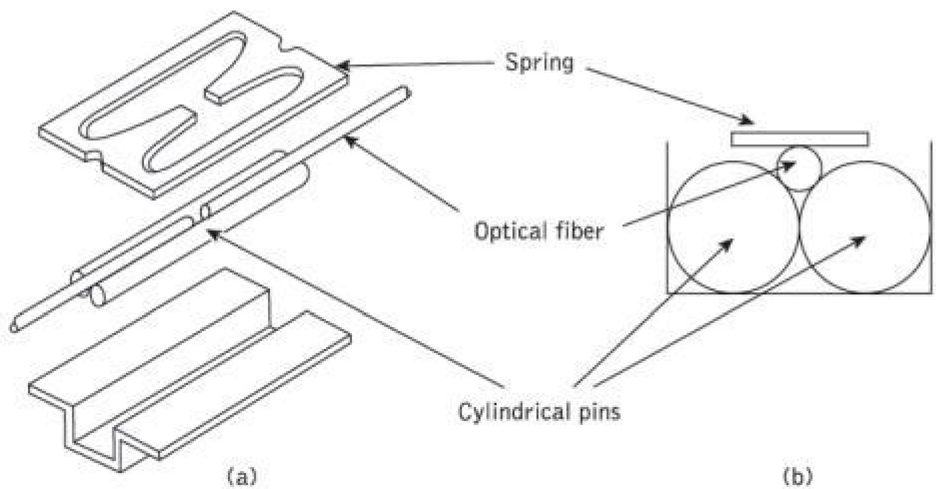


Figure 2.26 The Springroove splice: (a) expanded overview of the splice; (b) schematic cross-section of the splice

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.

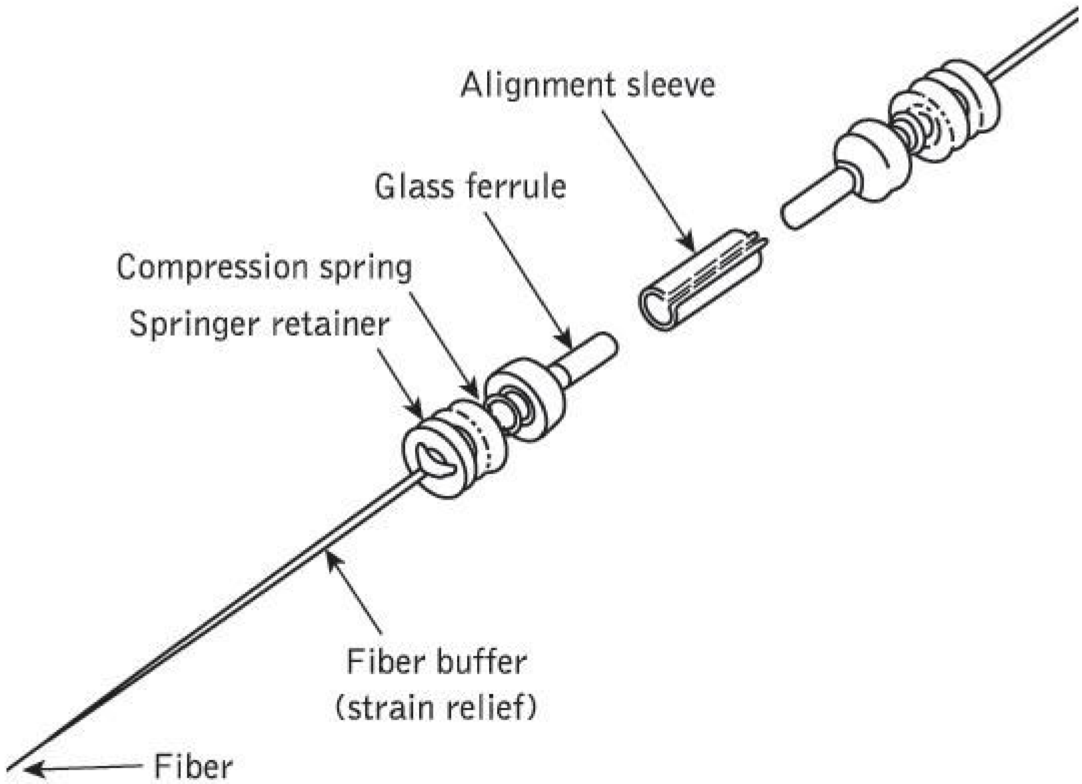


Figure 2.27 Multimode fiber mechanical splice using glass capillary tubes

3. Multiple splices

- Multiple simultaneous fusion splicing of an array of fibers in a ribbon cable has been demonstrated for both multimode and single-mode fibers. In both cases a 12-fiber ribbon was prepared by scoring and breaking prior to pressing the fiber ends onto a contact plate to avoid difficulties with varying gaps between the fibers to be fused.
- An electric are fusing device was then employed to provide simultaneous fusion. Such a device is now commercially available to allow the splicing of 12 fibers simultaneously in a time of around 6 minutes, which requires only 30 seconds per splice. Splice losses using this device with multimode graded index fiber range from an average of 0.04 dB to a maximum of 0.12 dB, whereas for single-mode fiber the average loss is 0.04 dB with a 0.4 dB maximum.

- A simple technique employed for multiple simultaneous splicing involves mechanical splicing of an array of fibers, usually in a ribbon cable. The V-groove multiple-splice secondary element comprising etched silicon chips has been used extensively in the United States for splicing multimode fibers.
- In this technique a 12-fiber splice is prepared by stripping the ribbon and coating material from the fibers. Then the 12 fibers are laid into the trapezoidal* grooves of a silicon chip using a comb structure, as shown in Figure 2.28.

- The top silicon chip is then positioned prior to applying epoxy to the chip–ribbon interface. Finally, after curing, the front end face is ground and polished.
- The process is normally carried out in the factory and the arrays are clipped together in the field, putting index-matching silica gel between the fiber ends. The average splice loss obtained with this technique in the field is 0.12 dB, with the majority of the loss resulting from intrinsic fiber mismatch.
- Major advantages of this method are the substantial reduction in splicing time (by more than a factor of 10) per fiber and the increased robustness of the final connection.
- Although early array splicing investigations using silicon chips demonstrated the feasibility of connecting 12*12 fiber arrays, in practice only single 12-fiber ribbons have been spliced at one time due to concerns in relation to splice tolerance and the large number of telecommunication channels which would be present in the two-dimensional array.
- An alternative V-groove flat chip molded from a glass-filled polymer resin has been employed in France. Moreover, direct mass splicing of 12-fiber ribbons has also been accomplished [Ref. 63].
- In this technique simultaneous end preparation of all 24 fibers was achieved using a ribbon grinding and polishing procedure. The ribbons were then laid in guides and all 12 fibers were positioned in grooves in the glass-filled plastic.