5

Optical Fiber : Connectors, Joints, Couplers, Isolators and Measurement Techniques

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5.1. FIBER CONNECTORS

Before connecting one fiber with the other fiber in the fiber optic communication link, one must decide whether the joint should be permanent or demountable. Based on this, we have two types of joints. A permanent joint is done by **splice** and a demountable joint is done by **connector**.

Requirements of a Good Connector

1. At connector joint, it should offer low coupling losses.
2. Connectors of the same type must be compatible from one manufacturer to another.
3. In the fiber link, the connector design should be simple so that it can be easily installed.
4. Connector joint should not be affected by temperature, dust and moisture *i.e.,* it should have low environmental sensitivity.
5. It should be available at a lower cost and have a precision suitable to the application.

The **coupling of light energy** from one fiber to the other fiber using the connectors is based on :

- butt-joint alignment mechanism
- expanded beam mechanism.

DO YOU KNOW

Connectors are used to connect fibers to the terminal equipment.

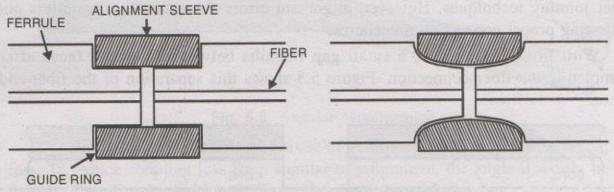
Figure 5.1 shows the butt-joint alignment type connectors used in both multimode and single mode fiber systems. These are straight sleeve (Fig. 5.1(*a*)) and the tapered sleeve (or) biconical sleeve connectors (Fig. 5.1(*b*)).

In the **straight sleeve connector,** there is a metal, ceramic or molded plastic ferrule for each fiber and the ferrule fits into the sleeve. The fiber is epoxied into the drilled hole of the ferrule.

In the **tapered sleeve connector** the length of the sleeve and a guide ring on the ferrules determine the end separation of the fibers. In the tapered sleeve connector, the ferrules and sleeves are tapered.

DO YOU KNOW

SMA connectors are commonly used with multimode fibers.



(*a*) *Straight Sleeve* (*b*) *Tapered Sleeve*

Fig. 5.1. Connectors Using Butt-Joint Alignment Designs.

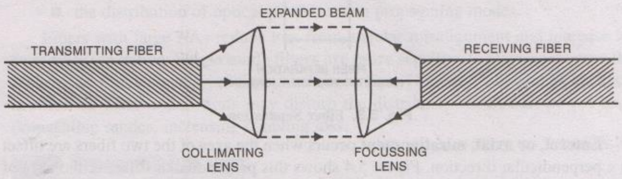


Fig. 5.2. Expanded Beam Connector.

Figure 5.2 shows the expanded beam connector employing collimating lens at the end of the transmitting fiber and focusing lens at the entrance end of the receiving fiber. The **collimating lens** collimating lens converts the light from the fiber into a parallel beam of light and the **focusing lens** converts the parallel beam of light into a focused beam of light on to the core of the receiving fiber.

- The fiber-to-lens distance is equal to the focal length of the lens.
- This expanded beam connector does not depend on lateral alignments and the optical processing elements can be easily inserted into the expanded beam between the fiber ends.
- The lenses are antireflection coated spherical micro lenses.
- To avoid losses due to fresnel reflection at the fiber-fiber joint, it is better to use 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, Fresnel reflection losses are completely eliminated.
- But if there is any angular misalignment between fibers, there is an increased loss for the fibers with index matching fluid than for the fibers with air gap.

5.2. FIBER TO FIBER JOINTS

A main source of extrinsic coupling loss in fiber-to-fiber connections is **poor fiber alignment.** The **three basic coupling errors that occur during fiber alignment** are :

- fiber separation (longitudinal misalignment).
- lateral misalignment.
- angular misalignment.

Most alignment errors are the result of mechanical imperfections introduced by fiber jointing techniques. However, alignment errors do result from installers not following proper connection procedures.

With **fiber separation**, a small gap remains between fiber-end faces after completing the fiber connection. Figure 5.3 shows this separation of the fiber-end faces.

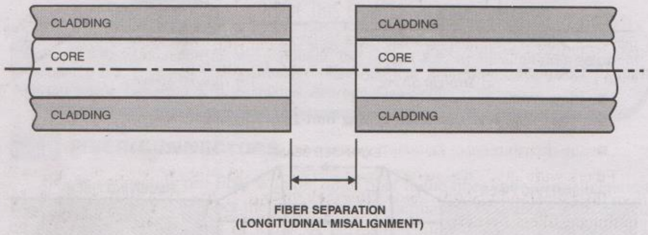
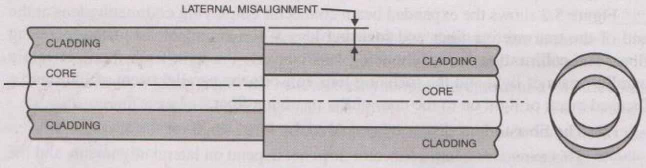


Fig. 5.3. Fiber Separation.

Lateral, or axial, misalignment occurs when the axes of the two fibers are offset in a perpendicular direction. Figure 5.4 shows this perpendicular offset of the axes of two connecting fibers.



(a) Side View *(b) End View*

Fig. 5.4. Lateral Misalignment.

Angular misalignment occurs when the axes of two connected fibers are no longer parallel. The axes of each fiber intersect at some angle (θ). Figure 5.5 shows the angular misalignment between the core axes.

Coupling loss caused by lateral and angular misalignment typically is greater than the loss caused by fiber separation. Loss, caused by fiber separation, is less critical because of the relative ease in limiting the distance of fiber separation. However, in some cases, fiber optic connectors prevent fibers from actual contact. These fiber optic connectors separate the fibers by a small gap. This gap eliminates damage to fiber-end faces during connection.

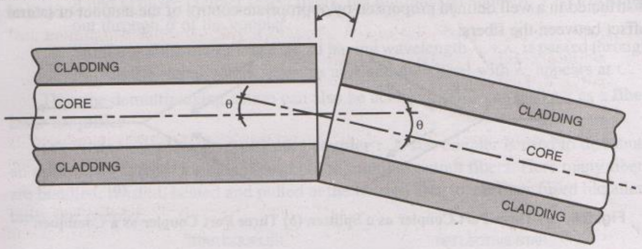


Fig. 5.5. Angular Misalignment.

For connectors with an air gap, the use of index matching gel reduces the coupling loss. To reduce coupling loss from angular misalignment, the angle θ should be less than 1°. **Coupling losses due to fiber alignment depend on:**

- fiber type
- core diameter
- the distribution of optical power among propagating modes.

Fibers with large NAs reduce loss from angular misalignment and increase loss from fiber separation. **Single mode fibers are more sensitive** to alignment errors than multimode fibers because of their small core size. However, **alignment errors in multimode fiber** connections may disturb the distribution of optical power in the propagating modes, increasing coupling loss.

5.3. FIBER COUPLERS

A coupler is a device which distributes light from a main fiber into one or more branch fibers.

There are **core interaction type couplers** and **surface interaction type couplers**.

In **core interaction type couplers,** the light energy transfer takes place through the core cross-section by butt jointing the fibers or by using some form of imaging optics between the fibers (*i.e.,* using lensing schemes such as rounded end fiber, a spherical lens used to image the core of one fiber on to the core area of the other fiber and a taper-ended fiber).

In **the surface interaction type** the light energy transfer takes place through the fiber surface and normal to the axis of the fiber by converting the guided core modes to cladding and refracted modes.

Different Types of Fiber Couplers and Their Functions

(*i*) **Three and four port couplers :** Figures 5.6(*a*) and 5.6(*b*) show the uses of a three port coupler as splitter and combiner of the signals. Light from the input fiber is coupled to the output fibers as shown in Fig. 5.6(*a*) or the light from the branch fibers are combined to form a single input to the output fiber.

For splitting, a single input fiber core is situated between the cores of two output fibers. This is called the **lateral offset method.** In this method, the input power can be distributed in a well defined proportion by appropriate control of the amount of lateral offset between the fibers.

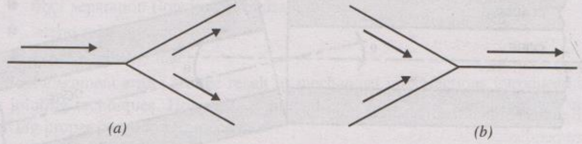


Fig. 5.6. *(a)* **Three Port Coupler as a Splitter.** *(b)* **Three Port Coupler as a Combiner.**

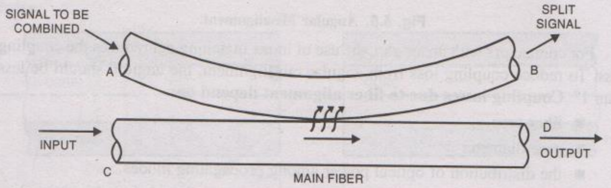


Fig. 5.7. Four Port Coupler.

Figure 5.7 shows the directional coupler which is a four port coupler. In this coupler, the fibers are generally twisted together and then spot fused under tension such that the fused section is elongated to form a biconical taper structure. It can act as a three port coupler or *T* coupler if one of the input ends or one of the output ends is closed. As shown in figure, each port is meant for different functions.

DO YOU KNOW

In Fresnel reflection, small portion of light may be reflected back into the transmitting fiber.

Inputs :

C – to pass the main signal into the main fiber.

A – to combine the extra signal or data into the main fiber.

Outputs :

D – to transmit the combined signal or remaining portion of the main signal through the main fiber.

B – to collect the split signal.

This type of coupler is based on the transfer of energy by surface interaction between the fibers. The amount of power taken from the main fiber or given to the main fiber depends on the length of the fused section of the fiber and the distance between the cores of the fused fibers.

This can also act as a wavelength division multiplexer provided that one of the output ends is closed.

- When *D* is closed and the signal at λ_1 and the signal at λ_2 are passed through *A* and *C* of the coupler respectively, the multiplexed signal $\lambda_1 + \lambda_2$ will come out through *B* of the coupler.
- Similarly if the multiplexed signal having wavelength $\lambda_1 + \lambda_2$ is passed through *B*, then the signal with λ_1 appears at *A* and the signal with λ_2 appears at *C*.

Thus the demultiplexing action can also be achieved. This can also act as a **fiber laser amplifier**.

(ii) **A star couplers or multi port coupler :** A star coupler is used to distribute an optical signal from a single input fiber to multiple output fibers. Here many fibers are bundled, twisted, heated and pulled at the twisted area to get fiber fused biconical taper star coupler.

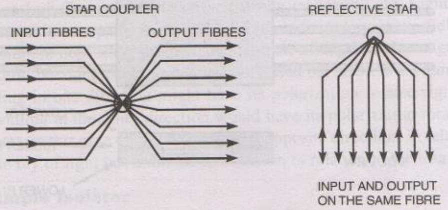


Fig. 5.8. Star Couplers

A star coupler is just a multi-way coupler where each input signal is made available on every output fiber. There are two basic types as shown in Figure 5.8. Star couplers have been the basis of a number of prototype optical LAN and MAN networks. The figure illustrates the function being performed rather than the way that function is achieved.

- First diagram shows an 8-way device where 8 inputs are mixed and made available on 8 outputs.
- Second diagram is a "reflective star" where input can be on any fiber and output is split equally among all fibers.

There are various ways of building star couplers:

(a) Fused-Fiber Star Couplers

In this technique many fibers are twisted together and heated under tension. The fibers melt together and become thinner as they are drawn out. The light mixes within the fused section. These couplers are mainly used for multimode operation. Figure 5.9 shows the design of fused fiber star coupler.

Fig. 5.9. Fused Fiber Star Coupler

(b) Mixing Plate

The mixing plate technique is illustrated in Figure 5.10. A fused silica plate is made in the form of a sandwich with a very thin (the same thickness as the fiber's core diameter) layer of higher RI glass in the middle. Fibers are attached to the edge so that the cores line up with the high RI (middle) part of the sandwich.

DO YOU KNOW

More recently single mode fiber couplers have been fabricated from polarization maintaining fiber.

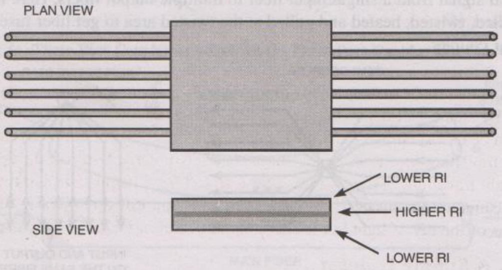


Fig. 5.10. Mixing plate coupler.

Entering light travels on a very large number of modes until it leaves through one of the exit fibers. This is essentially the same technique as is used in the planar free-space coupler but realized in fiber technology. It is suitable for either multimode or single-mode operation.

(c) Interconnection of Multiple Fiber 3 dB Couplers

This is illustrated in Figure 5.11. This is very easy to construct as it is only a matter of joining fused fiber couplers together. However, the assembly is quite unwieldy as fibers cannot be bent to very tight radii without unacceptable loss of light. Also its cost becomes exponentially greater with the number of required ports. This is linear with the number of couplers but of course the number of couplers needed grows exponentially.

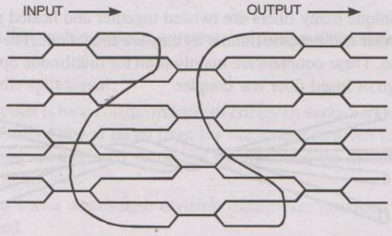


Fig. 5.11. Concatenation of multiple 3 dB couplers to form an 8-way star.

5.4. ISOLATORS

An isolator is a device that allows light to pass along a fiber in one direction but not in the opposite direction. Functionally it is very similar to a diode in the electrical world. Isolators are required in optical systems in many roles, the most common of which is the prevention of reflections coming back down a fiber from re-entering and disrupting the operations of a laser.

The Electro-optic Effect : Some materials such as lithium niobate ($LiNbO^3$) have variable refractive index characteristics depending on the strength of an applied electric field. Depending on the orientation of the electric field in relation to the crystal some materials also exhibit variable birefringence.

The Faraday Effect : The Faraday Effect is obtained when some materials such as YIG (Yttrium-Iron-Garnet) are placed in a strong magnetic field. Light travelling within the material has its plane of polarization (electric and magnetic field vectors) rotated by an amount depending on the length and the strength of the magnetic field. This can be useful but the most important aspect is that the effect is asymmetric. That is light travelling in one direction might have its polarization rotated right by (say) 45°. Light travelling in the other direction would have its polarization rotated left by the same amount (in this case 45°). The rotation is opposite directions in relation to the direction of the ray of light but in the same direction in relation to the rotator.

5.4.1. A Simple Isolator

Isolators are used in many situations to ensure that light only passes in one direction. This is necessary for example when coupling a laser to a fiber. Reflected light can cause instability in the laser and cause many undesirable effects. There are a number of ways of building isolators and most of these rely on one-way polarization effects.

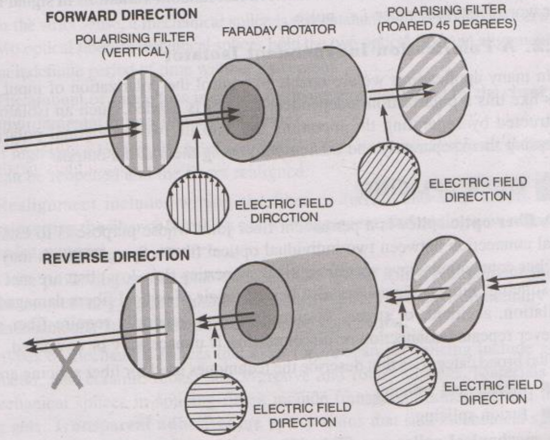


Fig. 5.12. Isolator operation.

Figure 5.12 shows the operation of a typical isolator. In the top of the figure light is passing in the "forward" direction from left to right across the page.

- Incoming light first meets a polarizing filter which removes all polarizations except those in the direction of the polarizer. On exit from the filter light is vertically polarized.
- Polarized input light then enters the Faraday rotator. This device rotates the polarization (without loss) by 45° to the right.
- The second polarizing filter is redundant in the forward direction. Light will pass through this filter now without loss as it is oriented in the same direction as the polarization of the incoming light.

The reverse direction is shown in the lower half of the figure.

- Light first meets a polarizer which filters out any light not oriented at 45° to the vertical. This is necessary as we can't be sure of the polarisation of unwanted reflections.
- The key to operation of the isolator is the Faraday rotator. In the reverse direction this device will rotate the polarization in the anti-clockwise direction (in relation to the direction of propagation). Thus operation of the rotator is asymmetric.
- On exit from the Faraday rotator light is now polarised at 90° from the vertical. When it meets the next polarizing filter it will be eliminated (absorbed).

The problem with this type of isolator is that the input polarization needs to be matched to the orientation of the isolator. If input is unpolarized then we lose half of the signal (3 dB). If the signal is polarized and the orientation is wrong then we can lose all of the signal. If the polarization varies with time, the variations will be translated into variations in attenuation. This results in fast random variations in signal level—in other words—serious noise *i.e.,* noise.

5.4.2. A Polarisation Independent Isolator

In many applications we are unable to control the polarization of input light. In cases like this a polarization independent isolator is needed. Such an isolator can be constructed by separating the incoming ray into its two orthogonal polarizations, processing them separately and then re-combining them at the output.

5.5. FIBER SPLICING

A **fiber optic splice** is a permanent fiber joint whose purpose is to establish an optical connection between two individual optical fibers. System design may require that fiber connections have specific optical properties (low loss) that are met only by fiber-splicing. Fiber optic splices also permit repair of optical fibers damaged during installation, accident, or stress. System designers generally require fiber splicing whenever repeated connection or disconnection is unnecessary or unwanted.

Two broad categories that describe the techniques used for fiber splicing are there :

- mechanical splicing
- fusion splicing

A **mechanical splice** is a fiber splice where mechanical fixtures and materials perform fiber alignment and connection.

A **fusion splice** is a fiber splice where localized heat fuses or melts the ends of two optical fibers together. Each splicing technique seeks to optimize splice performance and reduce splice loss. Low-loss fiber splicing results from proper fiber end preparation and alignment.

DO YOU KNOW

Fiber splicing is used in long haul optical fiber links to join smaller fiber lengths.

Fiber splice alignment can involve :

- passive
- active fiber core alignment.

Passive alignment relies on precision reference surfaces, either grooves or cylindrical holes, to align fiber cores during splicing. **Active alignment** involves the use of light for accurate fiber alignment. Active alignment may consist of either monitoring the loss through the splice during splice alignment or by using a microscope to accurately align the fiber cores for splicing. To monitor loss either an optical source and optical power meter or an optical time domain reflectometer (OTDR) are used. Active alignment procedures produce low-loss fiber splices.

(1) Mechanical Splices

Mechanical splicing involves the use mechanical fixtures to align and connect optical fibers. Mechanical splicing methods may involve :

- passive core alignment
- active core alignment

Active core alignment produces a lower loss splice than passive alignment. However, **passive core alignment** methods can produce mechanical splices with acceptable loss measurements even with single mode fibers.

- In the strict sense, a mechanical splice is a permanent connection made between two optical fibers. Mechanical splices hold the two optical fibers in alignment for an indefinite period of time without movement.
- The amount of splice loss is stable over time and unaffected by the change in environmental or mechanical conditions.
- If high splice loss results from assembling some mechanical splices, the splice can be reopened and the fibers realigned.
- Realignment includes wiping the fiber or ferrule end with a soft wipe, reinserting the fiber or ferrule in a new arrangement, and adding new refractive index material.
- Once producing an acceptable mechanical splice, splice realignment should be unnecessary because most mechanical splices are environmentally and mechanically stable within their intended application.

The types of mechanical splices that exist for mechanical splicing include glass, plastic, metal, and ceramic tubes; and V-groove and rotary devices. Materials that assist mechanical splices in splicing fibers include transparent adhesives and index matching gels. **Transparent adhesives** are epoxy resins that seal mechanical splices and provide index matching between the connected fibers.

(2) Glass or Ceramic Alignment Tube Splices

Mechanical splicing may involve the use of a glass or ceramic alignment tube, or capillary. The inner diameter of this glass or ceramic tube is slightly larger than the outer diameter of the fiber. A transparent adhesive, injected into the tube, bonds the two fibers together. The adhesive also provides index matching between the optical fibers. Figure 5.13 illustrates fiber alignment using a glass or ceramic tube. This splicing technique relies on the inner diameter of the alignment tube. If the inner diameter is too large, splice loss will increase because of fiber misalignment. If the inner diameter is too small, it is impossible to insert the fiber into the tube.

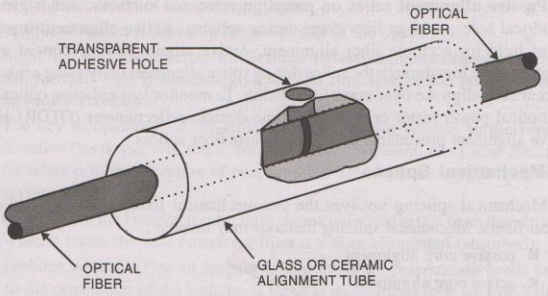


Fig. 5.13. A Glass or ceramic alignment tube for mechanical splicing.

(3) V-Grooved Splices

Mechanical splices may also use :

- a grooved substrate
- positioning rods to form suitable V-grooves for mechanical splicing.

The basic V-grooved device relies on an open grooved substrate to perform fiber alignment. When inserting the fibers into the grooved substrate, the V-groove aligns the cladding surface of each fiber end. A transparent adhesive makes the splice permanent by securing the fiber ends to the grooved substrate. Figure 5.14 illustrates this type of open V-grooved splice.

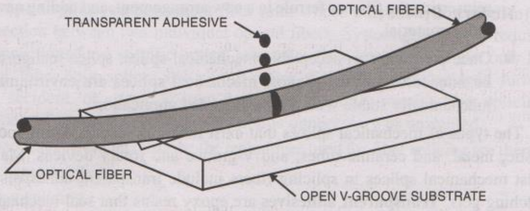


Fig. 5.14. Open V-grooved splice.

- V-grooved splices may involve sandwiching the butted ends of two prepared fibers between a V-grooved substrate and a flat glass plate.
- Additional V-grooved devices use two or three positioning rods to form a suitable V-groove for splicing.
- The V-grooved device that uses two positioning rods is the spring V-grooved splice. This splice uses a groove, formed by two rods positioned in a bracket to align the fiber ends.
- The diameter of the positioning rods permit the outer surface of each fiber end to extend above the groove formed by the rods.
- A flat spring presses the fiber ends into the groove maintaining fiber alignment.
- Transparent adhesive completes the assembly process by bonding the fiber ends and providing index matching.

Figure 5.15 is an illustration of the spring V-grooved splice. A variation of this splice uses a third positioning rod instead of a flat spring. The rods are held in place by a heat-shrinkable band, or tube.

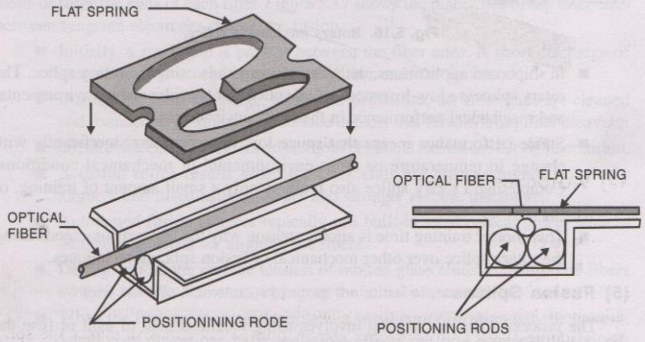


Fig. 5.15. Spring V-grooved mechanical splice.

(4) Rotary Splices

In a rotary splice, the fibers are mounted into a glass ferrule and secured with adhesives. The splice begins as one long glass ferrule that is broken in half during the assembly process. A fiber is inserted into each half of the tube and epoxied in place using an ultraviolet cure epoxy. The end face of the tubes are then polished and placed together using the alignment sleeve. Figure 5.16 is an illustration of a rotary splice.

- The fiber ends retain their original orientation and have added mechanical stability since each fiber is mounted into a glass ferrule and alignment sleeve.
- The rotary splice may use index matching gel within the alignment sleeve to produce low-loss splices.

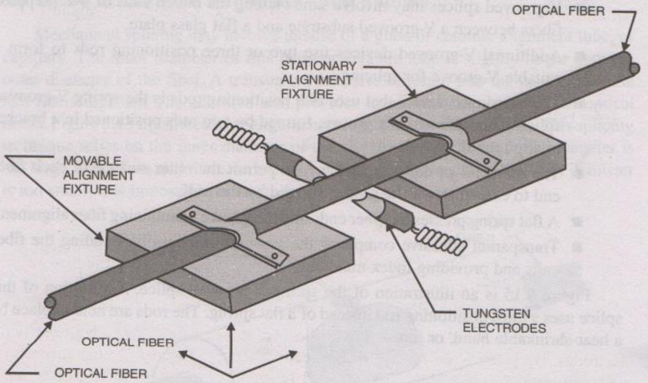


Fig. 5.16. Rotary mechanical splice.

- In shipboard applications, the Navy recommends using the rotary splice. The rotary splice is a low-loss mechanical splice that provides stable environmental and mechanical performance in the Navy environment.
- Stable performance means that splice loss does not vary significantly with change in temperature or other environmental or mechanical conditions. Completing a rotary splice also requires only a small amount of training, or expertise.
- This shorter training time is another reason why the Navy recommends using the rotary splice over other mechanical or fusion splicing techniques.

(5) Fusion Splices

The process diffusion splicing involves using localized heat to melt or fuse the ends of two optical fibers together. The splicing process begins by preparing each fiber end for fusion. Fusion splicing requires that all protective coatings should be removed from the ends of each fiber. The fiber is then cleaved using the score-and-break method. The quality of each fiber end is inspected using a microscope. In fusion splicing, splice loss is a direct function of the angles and quality of the two fiber-end faces.

The basic fusion splicing apparatus consists of two fixtures on which the fibers are mounted and two electrodes. Figure 5.17 shows a basic fusion-splicing apparatus. An inspection microscope assists in the placement of the prepared fiber ends into a fusion-splicing apparatus. The fibers are placed into the apparatus, aligned, and then fused together. Initially, fusion splicing used nichrome wire as the heating element to melt or fuse fibers together. New fusion-splicing techniques have replaced the nichrome wire with carbon dioxide (CO_2) lasers, electric arcs, or gas flames to heat the fiber ends, causing them to fuse together. The small size of the fusion splice and the development of automated fusion-splicing machines have made **electric arc fusion** (arc fusion), one of the most popular splicing techniques in commercial applications.

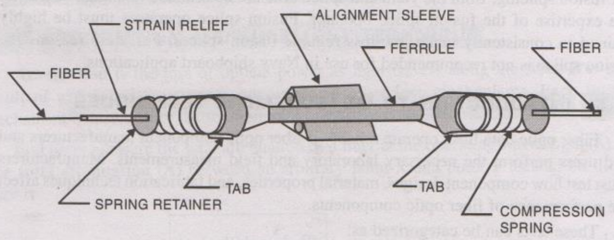


Fig. 5.17. A Basic fusion splicing apparatus.

Arc fusion involves the discharge of electric current across a gap between two electrodes. By placing the fiber ends between the electrodes, the electric discharge melts or fuses the ends of each fiber. Figure 5.17 shows the placement of the fiber ends between tungsten electrodes during arc fusion.

- Initially, a small gap is present between the fiber ends. A short discharge of electric current is used to prepare the fiber ends for fusion.
- During this short discharge, known as **profusion**, the fiber ends are cleaned and rounded to eliminate any surface defects that remain from fiber cleaving.
- Surface defects can cause core distortions or bubble formations during fiber fusion.
- A fusion splice results when the fiber ends are pressed together, actively aligned, and fused using a longer and stronger electric discharge.
- Automated fusion splicers typically use built-in local optical power launch/detection schemes for aligning the fibers.
- During fusion, the surface tension of molten glass tends to realign the fibers on their outside diameters, changing the initial alignment.
- When the fusion process is complete, a small core distortion may be present. Small core distortions have negligible effects on light propagating through multimode fibers.
- However, a small core distortion can significantly affect single mode fiber splice loss. The core distortion, and the splice loss, can be reduced by limiting the arc discharge and decreasing the gap distance between the two electrodes.
- This limits the region of molten glass. However, limiting the region of molten glass reduces the tensile strength of the splice.
- Fusion splicing yields typically vary between 25 and 75 percent depending on the strength and loss requirements for the splice and other factors.
- Other factors affecting splice yields include the condition of the splicing machine, the experience of the splice personnel, and environmental conditions.
- Since fusion splicing is inherently permanent, an unacceptable fusion splice requires breakage and refabrication of the splice.

In general, fusion splicing takes a longer time to complete than mechanical splicing. Also, yields are typically lower making the total time per successful splice much longer for fusion splicing. Both the yield and splice time are determined to a large degree by the expertise of the fusion splice operator. Fusion splice operators must be highly trained to consistently make low-loss reliable fusion splices. For these reasons the fusion splice is not recommended for use in Navy shipboard applications.

5.6. INTRODUCTION TO MEASUREMENT TECHNIQUES

Fiber optic data links operate reliably if fiber optic component manufacturers and end users perform the necessary laboratory and field measurements. Manufacturers must test how component designs, material properties, and fabrication techniques affect the performance of fiber optic components.

These tests can be categorized as:

- Design tests.
- Quality control tests.

Design tests are conducted during the development of a component. Design tests characterize the component's performance (optical, mechanical, and environmental) in the intended application. Once the component performance is characterized, generally the manufacturer only conducts quality control tests.

Quality control tests verify that the parts produced are the same as the parts the design tests were conducted on.

Whenever a measurement is made, it should be made using a standard measurement procedure. For most fiber optic measurements, these standard procedures are documented by the **Electronics Industries Association/Telecommunications Industries Association (EIA/TIA)**. Each component measurement procedure is assigned a unique number given by **EIA/TIA-455-X**. The X is a sequential number assigned to that particular component test procedure.

Laboratory Measurements

Providing a complete description of every laboratory measurement performed by manufacturers and end users is impossible. This chapter only provides descriptions of optical fiber and optical connection measurements that are important to system operation. Some of the optical fiber and optical connection laboratory measurements are as :

- Attenuation
- Cutoff wavelength (single mode)
- Bandwidth (multimode)
- Chromatic dispersion
- Fiber geometry
- Core diameter
- Numerical aperture (multimode)
- Mode field diameter (single mode)
- Insertion loss
- Return loss and reflectance

End users routinely perform optical fiber measurements to measure fiber power loss and fiber information capacity. End users may also perform optical fiber measurements to measure fiber geometrical properties.

5.7. ATTENUATION MEASUREMENT TECHNIQUE

Attenuation is the loss of optical power as light travels along the fiber. It is a result of absorption, scattering, bending, and other loss mechanisms. Each loss mechanism contributes to the total amount of fiber attenuation.

End users measure the total attenuation of a fiber at the operating wavelength (λ). The **total attenuation** (A) between an arbitrary point X and point Y located on the fiber is

$$\boxed{A = 10 \log \frac{P_x}{P_y} \text{ dB}} \qquad \text{...(5.1)}$$

where, P_x = The power output at point X.
P_y = The power output at point Y.

Point X is assumed to be closer to the optical source than point Y. The total amount of attenuation will vary with changes in wavelength λ.

The **attenuation coefficient** (α) or **attenuation rate**, is

$$\boxed{\alpha = \frac{A}{L} \text{ dB/km}} \qquad \text{...(5.2)}$$

where, L = The distance between points X and Y.
α = A positive number because P_x is always larger than P_y.

The attenuation coefficient will also vary with changes in λ.

Cutback Method

In laboratory situations, end users perform the cutback method for measuring the total attenuation of an optical fiber. The cutback method involves comparing the optical power transmitted through a long piece of test fiber to the power present at the beginning of the fiber.

The cutback method for measuring **multimode fiber attenuation is EIA/TIA-455-46**. The cutback method for measuring **single mode fiber attenuation is EIA/TIA-455-78.**

The basic measurement process is same for both of these procedures. The test method requires that the test fiber of known length (L) be cut back to an approximate 2-m length. This cut back causes the destruction of 2-m of fiber. This method requires access to both fiber ends. Each fiber end should be properly prepared to make measurements.

Figure 5.18 illustrates the cutback method for measuring fiber attenuation. The cutback method begins by measuring, with an optical power meter, the output power P_1 of the test fiber of known length (L) (Fig. 5.18(*a*)). Without disturbing the input light conditions, the test fiber is cut back to an approximate 2-m length. The output power P_2 of the shortened test fiber is then measured (Fig. 5.18(*a*)). The fiber attenuation AT and the attenuation coefficient a are then calculated.

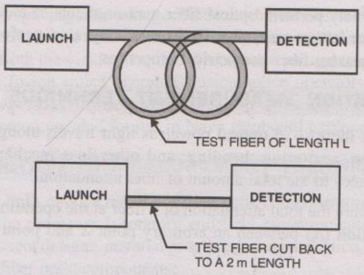


Fig. 5.18. Cutback Method for Measuring Fiber Attenuation : *(a)* **Test measurement;** *(b)* **Cut-back Measurement.**

Launch Conditions

Measurement personnel must pay attention to how optical power is launched into the fiber when measuring fiber attenuation. Different distributions of launch power can result in different attenuation measurements. This is a **major problem with multimode fiber than single mode fiber**.

- For **single mode fiber**, optical power must be launched only into the fundamental mode. This is done by using a mode filter on the fiber.
- For **multimode fiber**, the distribution of power among the modes of the fiber must be controlled. This is accomplished by controlling the launch spot size and angular distribution.

The **launch spot size** is the area of the fiber face illuminated by the light beam from the optical source. The diameter of the spot depends on the size of the optical source and the properties of the optical elements (lenses, and so on) between the source and the fiber end face.

The **angular distribution** is the angular extent of the light beam from the optical source incident on the fiber end face. The launch angular distribution also depends on the size of the optical source and the properties of the optical elements between the optical source and the fiber end face.

A **mode filter** is a device that attenuates specific modes propagating in the core of an optical fiber. Mode filters generally involve wrapping the test fiber around a mandrel. For multimode, tight bends tend to remove high-order modes from the fiber. This type of mode filter is known as a **mandrel wrap mode filter**.

- For multimode fibers, mode filters remove high-order propagating modes and are individually tailored and adjusted for a specific fiber type.
- For single mode fibers, a mode filter is used to eliminate the second-order mode from propagating along the fiber. The propagation of the second-order mode will affect attenuation measurements.

5.8. DISPERSION MEASUREMENT TECHNIQUE

Dispersion reduces the bandwidth or information-carrying capacity of an optical fiber. **Dispersion** causes the spreading of the light pulse as it travels along the fiber.

Fiber dispersion mechanisms include:

- Intramodal (chromatic) dispersion.
- Intermodal (modal) dispersion.

Multimode fiber bandwidth is a measure of the intermodal dispersion of the multimode fiber. Intermodal dispersion is maximum when all fiber modes are excited. The source used for intermodal dispersion measurements must overfill the fiber. The optical source must also have a narrow spectral width to reduce the effects of chromatic dispersion in the measurement.

There are **two basic techniques** for measuring the modal bandwidth of an optical fiber.

- The first technique characterizes dispersion by measuring the **impulse response** ***h*(*t*)** of the fiber in the time domain.
- The second technique characterizes modal dispersion by measuring the **baseband frequency response** ***H*(*f*)** of the fiber in the frequency domain.

$H(f)$ is the **power transfer function** of the fiber at the base band frequency (f). $H(f)$ is also the Fourier transform of the power impulse response $h(t)$. Only the frequency response method is described here.

The test method for measuring the bandwidth of multimode fibers in the frequency domain is EIA/TIA-455-30. Signals of varying frequencies (f) are launched into the test fiber and the power exiting the fiber at the launched fundamental frequency measured. This optical output power is denoted as $P_{out}(f)$. The test fiber is then cut back or replaced with a short length of fiber of the same type. Signals of the same frequency are launched into the cut-back fiber and the power exiting the cut-back fiber at the launched fundamental frequency measured. The optical power exiting the cutback or replacement fiber is denoted as P_{in} (f).

The **magnitude of the optical fiber frequency response** is

$$\boxed{H(f) = \log_{10}\left[\frac{P_{out}(f)}{P_{in}(f)}\right]} \qquad ...(5.3)$$

The **fiber bandwidth** is defined as the lowest frequency at which the magnitude of the fiber frequency response has decreased to one-half its zero-frequency value. This is the –3 decibel (dB) optical power frequency (f_{3dB}). This frequency is known as the fiber bandwidth. Bandwidth is normally given in units of megahertz-kilometers (MHz-km).

5.9. FIBER REFRACTIVE INDEX PROFILE MEASUREMENT TECHNIQUE

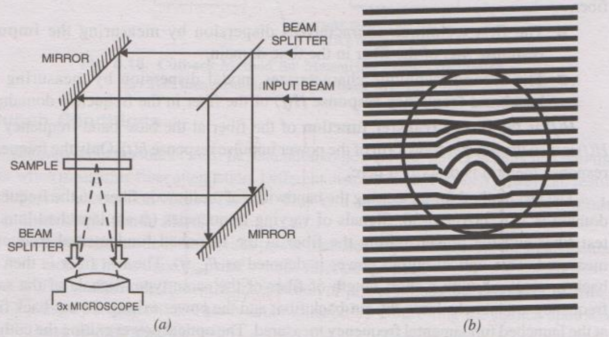
Fiber core refractive index profile plays an important role in characterizing the properties of optical fibers. It allows determination of the fiber's numerical aperture and the number of modes propagating within the fiber core. In this section, we will discuss some of the more popular methods used.

5.9.1. Interferometric Methods

Interference microscopes (*e.g.*, Mach Zehnder, Michelson) has been widely used to determine the refractive index profiles of optica fibers. This technique involves the preparation of a thin slice of fiber which has both ends accurately polished to obtain square and optically flat surfaces. Often this slab is immersed in an index matching fluid, and the assembly is examined with an interference microscope. **Two major methods are employed** using :

- A transmitted light inferometer (Mach-Zehnder)
- A reflected light interferometer (Michelson).

The both cases light from the microscope travels normal to the prepared fiber slice faces and differences in refractive index result in different optical path lengths. This situation is shown in Fig. 5.19(*a*). When the phase of incident light is compared with the phase of the emerging light, a field of parallel interference fringes is observed. An example of which is shown in Fig. 5.19(*b*).



(*a*) (*b*)

Fig. 5.19. (*a*) **The Principle of the Mach-Zehnder Interferometer. The Interference Fringe Pattern Obtained With an Interference Microscope from a Graded Index Fiber.**

Within the fiber core, the fringe displacements for the points are measured using as references the parallel fringes outside the fiber core. The refractive index difference between a point in the fiber core and cladding can be obtained from the fringe shift *q*, which corresponds to a number of fringe displacements. The **difference in refractive index δ_n** is given by

$$\boxed{\delta_n = \frac{q\lambda}{x}} \qquad ...(5.4)$$

where, x = Thickness of the fiber slab

λ = Incident optical wavelength

The slab method gives an accurate measusurement of the refractive index profile. A **limitation** of this method is the time required to prepare the fiber slab.

Another interferometric technique has been developed which does not require any sample preparation. Here the light beam is incident to the fiber perpendicular to its axis, this is known as **transverse shearing interferometry.**

5.9.2. Near Field Scanning Method

This method utilizes the close resemblance that exists between the near field intensity distribution and the refractive index profile, for a fiber with all the guided modes equally illuminated. This is a straight forward and rapid method for acquiring the refractive index profile.

When a diffuse Lambertion source is used to excite all the guided modes than the near field optical power density at a radius *r* from the core axis $P_D(r)$ may be expressed as a fraction of the core axis near field optical power density $P_D(0)$ *i.e.*,

$$\boxed{\frac{P_D(r)}{P_D(0)} = C(r, z)\left[\frac{n_1^2(r) - n_2^2}{n_1^2(0) - n_2^2}\right]} \qquad ...(5.5)$$

where, $n_1(0)$ and $n_1(r)$ = Refractive indices at the core axis and at a distance *r* from the core axis respectively.

n_2 = Cladding refractive index

$C(r, 2)$ = Correction Factor.

Figure 5.20 shows its experimental configuration.

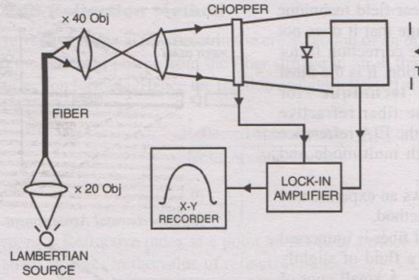
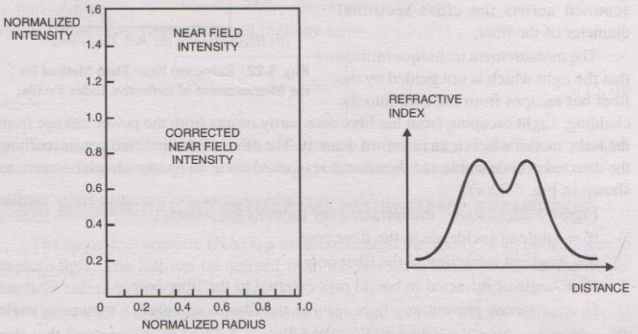


Fig. 5.20. Experimental Setup for the Near Field Scanning Measurement of the Refractive Index Profile.



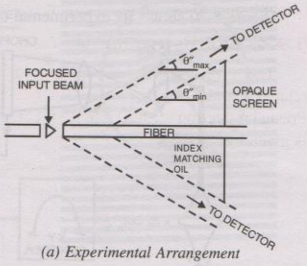
(*a*) (*b*)

Fig. 5.21.

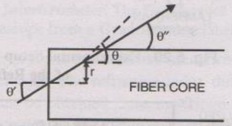
The output from a Lambertion source is focused on to the end of the fiber using a microscope objective lens. A magnified image of the fiber output end is displayed in the plane of a small active area photodetector. The photodetector scans the field transversely receives amplification from the phase sensitive combination of the optical chopper and lockin amplifier. Hence the profile may be plotted directly on the ***X-Y* recorder.**

The profile must be corrected w.r.t. $C(r, z)$ as shown in Fig. 5.21(*a*) which is very time consuming. The scanning and data acquisition, both can be automated with the inclusion of a minicomputer. Figure 5.21(*b*) shows a typical refractive index profile for a practical step index fiber measured by the near field scanning method. It may be observed that the profile dips in the center at the fiber core axis.

5.9.3. Refracted Near Field Method



(*a*) *Experimental Arrangement*



(*b*) *Illustration of the Ray Trajectories.*

Fig. 5.22. Refracted Near Field Method for the Measurement of Reflective Index Profile.

The refracted near field (RNF) or refracted ray method is complementary to the transmitted near field technique but it has a **advantage** that it does not require a leaky mode correction factor or equal mode excitation. It is the **most commonly used technique** for determination of the fiber refractive index profile and is the EIA refrerence test method for both multimode and single mode fibers.

Figure 5.22 shows an experimental setup for the RNF method.

A short length of fiber is immersed in a cell containing a fluid of slightly high refractive index. A small spot of light is emitted from 633 nm helium neon laser. For best resolution it is scanned across the cross-sectional diameter of the fiber.

The measurement technique utilizes that the light which is not guided by the fiber but escapes from the core into the cladding. Light escaping from the fiber core partly results from the power leakage from the leaky modes which is an unknown quantity. The effect of this radiated power reaching the detected is undesirable and therefore it is blocked using an opaque circular screen, as shown in Fig. 5.22(*a*).

Figure 5.22(*b*) shows the refracted ray trajectories, where,

θ' = Angle of incidence in the fiber core

θ = Angle of refraction in the fiber core

θ'' = Angle of refracted in bound rays external to the fiber core

Opaque screen prevent any light leaving the fiber core below a minimum angle θ''_{min} from reaching the detector. From the Figure 5.22(*b*), it is observed that this minimum angle corresponds to a minimum angle of incidence θ'_{min}. Therefore all light at an angle of incidence $\theta' > \theta'_{min}$ must be allowed to reach the detector.

The detected optical power as a function of the radial position of the input beam $P(r)$, is measured and a value $P(a)$ corresponding to the input beam being focussed into the cladding is also obtained.

The refractive index profile $n(r)$ for the fiber core is given by :

$$\boxed{n(r) = n_2 + n_2 \cos\theta''_{min} (\cos\theta''_{min} - \cos\theta'_{max}) \left[\frac{P(a) - P(r)}{P(a)}\right]} \qquad ...(5.6)$$

where, n_2 = Cladding refractive index

Equation (5.6) can be written as

$$\boxed{n(r) = K_1 - K_2 P(r)} \qquad ...(5.7)$$

It is clear that $n(r)$ is proportional to $P(r)$ and hence the measurement system can be calibrated to obtain the constants K_1 and K_2.

5.9.4. End Reflection Method

The refractive index at any point in the cross section of an optical fiber is directly related to the reflected power from the fiber surface in air at that point following the Fresnel reflection formula. Hence the fraction of light reflected at the air fiber interface is given by

$$r = \frac{\text{Reflected optical power}}{\text{Incident optical power}}$$

$$r = \left(\frac{n_1 - 1}{n_1 + 1}\right)^2 \qquad ...(5.8)$$

where, n_1 = Refractive index at a point on the fiber surface.

For small changes in the value of refractive index

$$\boxed{\delta r = 4 \frac{n_1 - 1}{(n_1 + 1)^3} \delta n_1} \qquad ...(5.9)$$

By combining Eqns. (5.8) and (5.9) we have

$$\boxed{\frac{\delta r}{r} = \left[\frac{4}{n_1^2 - 1}\right] \delta n_1} \qquad ...(5.10)$$

Equation (5.10) gives the relative change in the Fresnel co-efficient r which corresponds to the change of refractive index at that point of measurement.

5.10. NUMERICAL APERTURE MEASUREMENT TECHNIQUE

The numerical aperture (NA) is a measurement of the ability of an optical fiber to capture light. The NA can be defined from the refractive index profile or the output far-field radiation pattern.

The NA of a multimode fiber having a near-parabolic refractive index profile is measured using EIA/TIA-455-177. In EIA/TIA-455-177, the fiber NA is measured from the output far-field radiation pattern. The far-field power distribution describes the emitted power per unit area in the far-field region. The far-field region is the region far from the fiber-end face. The far-field power distribution describes the emitted power per unit area as a function of angle Θ some distance away from the fiber-end face. The distance between the fiber-end face and detector in the far-field region is in the centimeters (cm) range for multimode fibers and millimeters (mm) range for single mode fibers.

EIA/TIA-455-47 describes various procedures, or methods, for measuring the far-field power distribution of optical waveguides. These procedures involve either an angular or spacial scan. Figure 5.23 shows an angular and spacial scan for measuring the far-field power distribution.

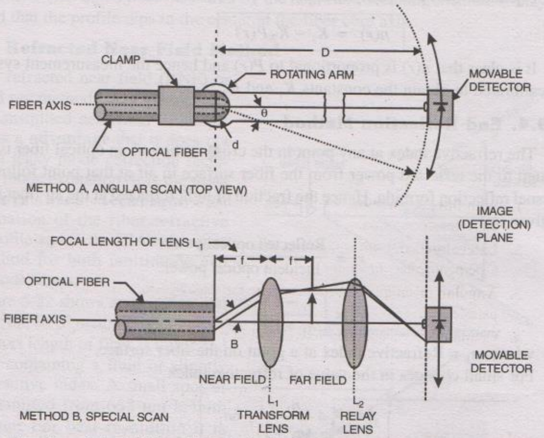


Fig. 5.23. Angular and Spacial Scan Methods for Measuring the Far-field Power Distribution.

Figure 5.23(*a*) illustrates a far-field angular scan of the fiber-end face by a rotating detector. The fiber output radiation pattern is scanned by a rotating detector in the far-field. The detector rotates in a spherical manner. A record of the far-field power distribution is kept as a function of angle Θ.

Figure 5.23(*b*) illustrates a far-field spacial scan of the fiber-end face by a movable (planar) detector. In a far-field spacial scan, lens L_1 performs a Fourier transform of the fiber output near-field pattern. A second lens, L_2, is positioned to magnify and relay the transformed image to the detector plane. The image is scanned in a plane by a movable detector. The scan position y in the Fourier transform plane is proportional to the far-field scan angle Θ.

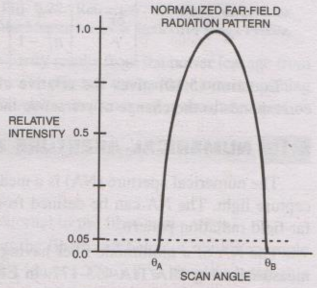


Fig. 5.24. Normalized Far-Field Radiation Pattern.

A record of the far-field power distribution is kept as a function of the far-field scan angle.

The normalized far-field pattern is plotted as a function of the far-field scan angle Θ as shown in Figure 5.24.

Fiber NA is defined by the 5 percent intensity level, or the 0.05 intensity level, as shown in Fig. 5.24. The 0.05 intensity level intersects the normalized curve at scan angles Θ_A and Θ_B.

The **fiber** ***NA*** is defined as

$$\boxed{NA = \sin \Theta_5} \qquad \text{...(5.11)}$$

where, Θ_5 = The 5 percent intensity half angle.

Θ_5 = is determined from Θ_A and Θ_B as shown below :

$$\boxed{\Theta_5 = \frac{\Theta_A - \Theta_B}{2}} \qquad \text{...(5.12)}$$

Summary

1. With **fiber separation**, a small gap remains between fiber-end faces after completing the fiber connection.
2. **Lateral or axial, misalignment** occurs when the axes of the two fibers are offset in a perpendicular direction.
3. **Angular misalignment** occurs when the axes of two connected fibers are no longer parallel.
4. Coupling loss caused by lateral and angular misalignment typically is greater than the loss caused by fiber separation. Loss, caused by fiber separation, is less critical because of the relative ease in limiting the distance of fiber separation.
5. **Coupling losses due to fiber alignment depend on:**
   - fiber type
   - core diameter
   - the distribution of optical power among propagating modes.
6. Two broad categories that describe the techniques used for fiber splicing are there :
   - mechanical splicing
   - fusion splicing
7. A **mechanical splice** is a fiber splice where mechanical fixtures and materials perform fiber alignment and connection.
8. A **fusion splice** is a fiber splice where localized heat fuses or melts the ends of two optical fibers together.
9. **Fiber splice alignment** can involve :
   - passive
   - active fiber core alignment.
10. **Passive alignment** relies on precision reference surfaces, either grooves or cylindrical holes, to align fiber cores during splicing.
11. **Active alignment** involves the use of light for accurate fiber alignment. Active alignment may consist of either monitoring the loss through the splice during splice alignment or by using a microscope to accurately align the fiber cores for splicing.