Chapter 9

Distribution Networks and Fiber Components

- Up to now we have been considering, at least implicitly, only **point-to-point** unidirectional links.
- However, the versatility of fiber optics makes possible the design of **bidirectional** systems, which propagate signals on a single fiber in **both directions simultaneously.**
- Also, **distribution** of information over fibers to multiple terminals is important and practical.
- Multi-terminal architectures have many applications.
- The most important might be the *local-area network* (**LAN**), an interconnection of numerous input and output devices that is located within a single building or a campus.
- An office LAN includes **video monitors** and **workstations** located throughout the business premises.
- From each terminal an employee can access a variety of equipment and services, such as electronic data files, word processor, video-text service, computer, computer printer, or copying machine.
- Computers themselves can be linked by a LAN.
- Facilities for **video teleconferencing** can also be included.
- In a fiber optic LAN, fibers carry the information between the connected devices.
- Advantages over wires include improved security, smaller size, lower weight, and broader bandwidth.
- In another application, LANs installed in manufacturing plants monitor and control operations.
- In this chapter we study **basic system configurations and components** for distributing and controlling information over fiber cables in ways that are not as restrictive as the single-optical-channel, unidirectional link connecting a single transmitter to a single receiver.

9-1 DISTRIBUTION NETWORKS

- A directional coupler forms the basis of many distribution networks. Fig 9.1 illustrates a four port directional coupler. Later we will discuss couplers with more ports.
- The directions of allowed power flow are indicated by the arrows in the figure. For a description of coupler characteristics, we will assume that power $P_{\}}$ is incident on port 1 of the coupler.

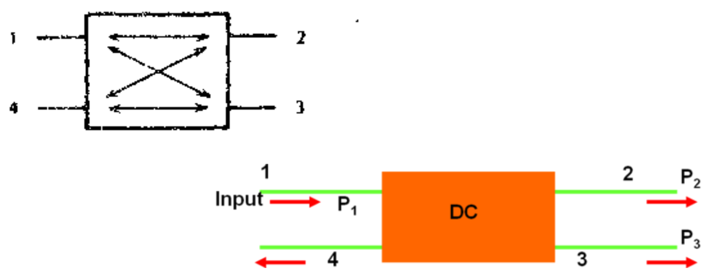

Fig 9-1 **four-port directional coupler (DC)**

- This power will **divide** between ports 2 and 3 according to the desired **splitting ratio.**
- Ideally, no power will reach port 4, the **isolated** port.
- Without loss of generality, we can assume that the power emerging from port 2 (P_2) is equal to, or greater than, the power emerging from port 3 (P_3).
- We then define the following **characteristics coupler losses** (in dB):

1. *Throughput loss*

$$L_{THP} = -10 \log (P_2 / P_1) \qquad (9\text{-}1)$$

specifies the amount of transmission loss between the input port and the **favored port** (port 2).

2. *Tap loss*

$$L_{TAP} = -10 \log (P_3 / P_1) \qquad (9\text{-}2)$$

specifies the transmission loss between the input port and the **tap** (port 3).

3. Directionality

$$L_D = -10 \log (P_4 / P_1) \qquad (9\text{-}3)$$

specifies the loss between the input port and the port we wish to **isolate** (port 4).

4. *Excess* loss

$$L_E = -10 \log [(P_2 + P_3) / P_1] \qquad (9\text{-}4)$$

specifies the power lost **within the coupler**. It includes **radiation, scattering, absorption, and coupling** to the isolated port.

- In an ideal coupler, no power reaches port 4 ($L_D = \infty$).
- Additionally, no power is lost, so the total power emerging from ports 2 and 3 equals the input power ***($P_2 + P_3 = P_1$),*** making the excess loss zero.
- Good directional couplers have excess losses less than 1 dB and directionality greater than 40 dB.

- The *splitting ratio* is P_2/P_3, the ratio of the powers at the two output ports.
- Couplers are often described by their tap loss. For example, a 10-dB coupler is one that has a 10-dB tap loss.
- Table 9-1 lists values of throughput loss, tap loss, and splitting ratio for several ideal couplers.
- For the lossless coupler, $\boldsymbol{P_2 = P_1 - P_3}$, so the throughput loss [Eq. (9-1)] can be written as

$$L_{THP} = -10 \log (1 - 10^{-L_{TAP}/10}) \qquad (9\text{-}5)$$

TABLE 9-1. Characteristics of Several ideal Four-Port Directional Couplers

Coupler Description	**TAP (dB)**	***THP (dB)**	**Splitting Ratio**
3dB	3	3	1 :1
6dB	6	1 25	3:1
10 dB	10	0.46	9:1
12 dB	12	0.28	15:1

- As indicated by the arrows in Fig. 9-1, the coupler is bidirectional. **Any of the** four ports can serve as the input.
- Possible couplings (with the favored port listed just after the input port) are 1 to 2 and 3, 2 to 1 and 4, 3 to 4 and 1, and 4 to 3 and 2.
- Directional couplers are normally constructed symmetrically, so the characteristic losses have the **same values** regardless of which port is chosen as the input.

Duplexing Network

- In the most straightforward scheme for transmitting and receiving **at both ends** of a point-to-point link, **two fibers** are used.
- One carries information in one direction, and the other carries signals in the opposite direction.
- A full-duplex system (one permitting simultaneous transmission in both directions along the **same fiber**) conserves fiber, a particularly significant advantage for long links.
- Figure 9-2 illustrates the full-duplex architecture with a **directional coupler** at each terminal. In this application, perfect 3-dB couplers would provide 6 dB of loss between the transmitter and receiver.
- Excess loss and the connector loss at each port would lower the received power even farther.

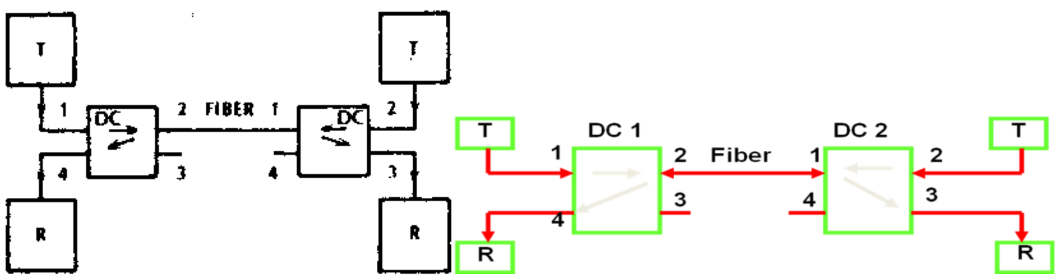

Figure 9-2 Full-duplex communications system. T, transmitter; *R,* receiver; DC, directional coupler. The unused ports are also shown.

Tee Network

- The ***tee*** network, drawn in Fig. 9-3, interconnects **many terminals**. Each terminal contains a transmitter and a receiver.

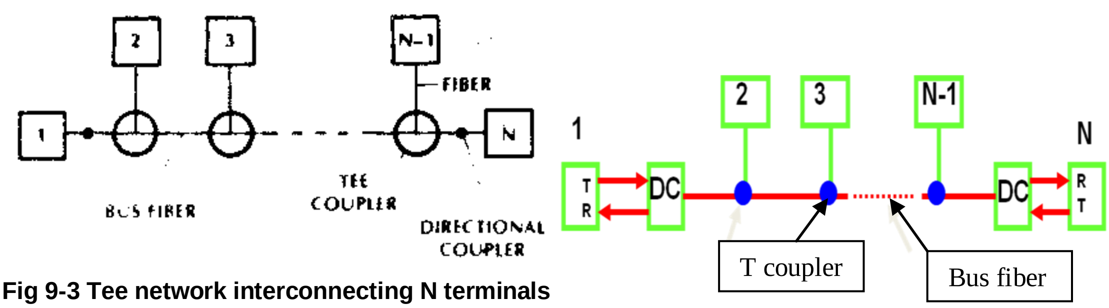

Fig 9-3 Tee network interconnecting N terminals

- A trunk fiber, also known a **bus**, or **data bus**, carries the information between **taps**.
- **Taps** are provided by **tee couplers**. The tee coupler shown in Fig. 9-4 permits bidirectional information flow in the bus fiber.

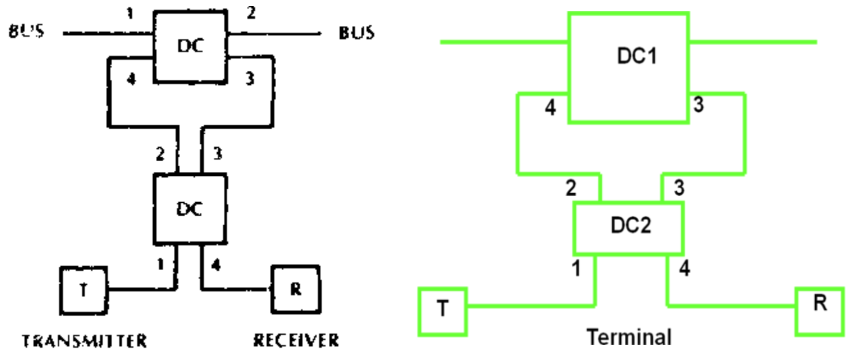

Fig 9-4 Tee Coupler using two directional coupler

- In the figure9.3, two directional couplers constitute the tee coupler. Terminals 1 and *N* are connected to the bus by a **single directional coupler**.
- A network with many terminals requires a large splitting ratio (throughput power >> tapped power) for the tee couplers.
- This ensures that signals reaching receivers far from the transmitter will have sufficient strength to be properly detected.

- In addition to loss, tee networks have **other characteristics** worth mentioning. These characteristics involve:
  - special receiver requirements,
  - susceptibility to damage, and
  - ease of adding new terminals.

- A terminal in a tee network will receive more power from an adjacent terminal than from a distant one.
- Therefore, the receiver must be able to process signals having a wide range of power levels. In other words, the receiver must have a large ***dynamic range.***
- Localized **damage** to a tee network does not shut off all communications. A break in the bus fiber **divides** the system into two parts, with information flow intact on each side of the break.
- Damage to **one of the tee** couplers divides the System and eliminates contact with the tapped terminal.
- Damage to a terminal merely disconnects that terminal, leaving the rest of the system in operation.
- New terminals can be added to a tee network **simply by** cutting the bus fiber and inserting a tee coupler.

Star Network

- An alternative to the tee, for multi-terminal networks, is the *star* configuration, drawn in Fig. 9-6.

- In this scheme, a ***transmissive star* coupler** interconnects *N* terminals.
- The coupler has *2N* ports.
- It may be viewed as a directional coupler with more than four ports.
- The star coupler distributes power equally to each of the receiver ports from any one of the transmitter ports, as illustrated in Fig. 9-7.
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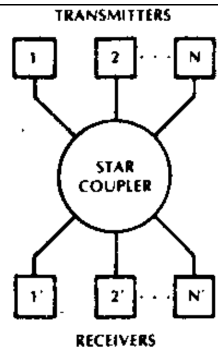
<td>
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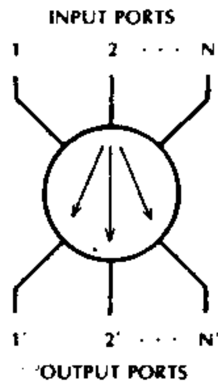
<td>
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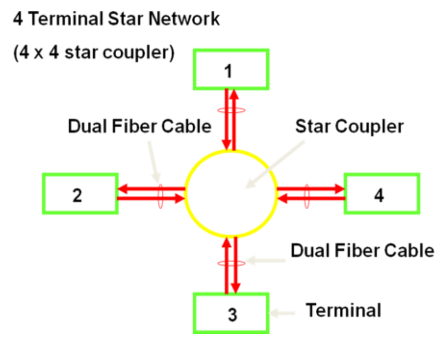
<td>
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<td>Fig 9.6 start network</td>
<td>Fig 9-7 A transmissive start coupler distributes power from any port to all the output ports.</td>
<td>4 terminal start network (4x4 start coupler)</td>
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- An ideal star divides the input power *N* ways without loss.
- The transmission efficiency for each port is then 1/N, and the corresponding insertion loss (in decibels) is

$$L_{IN} = -10 \log \frac{1}{N} \qquad (9\text{-}9)$$

- For the greater efficiency, the start coupler in a network having N terminals should have just 2N ports. That is all the ports should be in use.
- A coupler with more than 2N ports introduce more distribution loss.
- For this reason, addition of new terminals require a new start coupler.
- In a star network, damage to a branch cable connecting a terminal to the coupler merely interrupts service to that terminal, however destruction of the star coupler itself terminates all data flow.

Ring Network

- Fibers can also connect numerous terminals in the *ring* network illustrated by Fig. 9-9.
- The ring is actually a serial connection of independent point-to-point links. Each ring node contains an **optical transmitter and receiver**.
- The node's function is that of an active regenerator. After the receiver detects the delivered message and the station reads it, the data are **regenerated** and then retransmitted to the next station.
- In a ring, the power from any one optical transmitter travels to a single receiver.
- There is **no sharing** of the optical power by several stations, as is the case in the tee and star networks.
- For this reason, the ring can interconnect more terminals than any of the other networks described in this section.
- That is, the ring is not limited by power-distribution losses as are the tee and star.
- Of course, the active ring nodes are much more complex than the **passive** nodes of the tee and star.

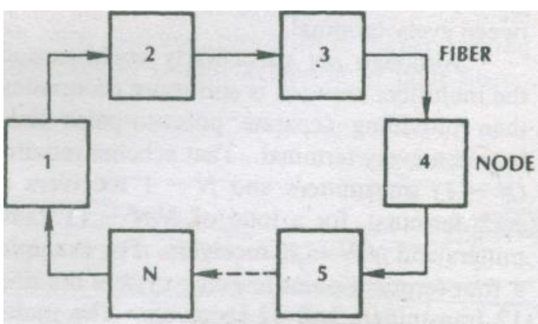
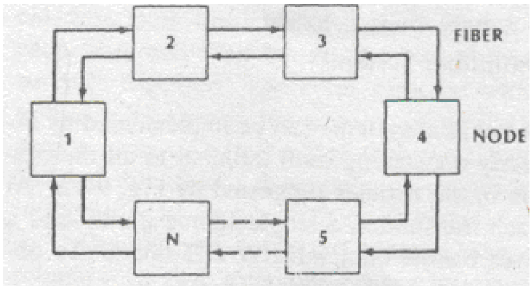
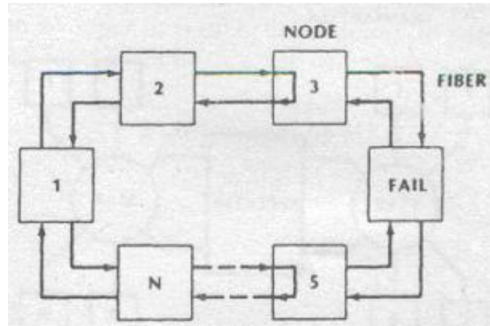


Figure 9-9 Ring network.

- If any one node in the ring fails, then the entire system shuts down.
- Similarly, the entire system fails if there is a break in any of the transmission fibers in the loop.
- Several **modifications** to the basic ring solve this problem. An optical ***bypass switch*** can be inserted that will direct the optical path around a failed node until repairs can be made.
- Electromechanical bypass switches designed for this purpose are described in Section 9-4.
- Installing a **second loop** is another practical modification of the basic ring.

- This architecture, drawn in Fig. 9 10, adds redundancy to the system. The second ring transmits in the **direction opposite** to that of the primary ring.

 	
a) Basic network	b)Reconfigured Network when node 4 has failed
Fig 9-10 Counter-rotating rings	

- Ordinarily, only the primary operates. However when a node or a fiber fails, the system wraps the signal around so that a complete loop is still possible.
- Figure 9-10(b) shows the signal path when a failure has occurred and the network has reconfigured itself.
- The fiber distributed-data interface (FDDI) local-area network uses the dual ring architecture.

Hybrid Distribution Systems

- Combinations of **tee** and **star** networks provide flexibility in the design of multi-terminal fiber systems.
- In a star-tee network, a star might link closely spaced units and a linear tee might connect more distant terminals.
- A direct connection between the star and tee may be made. An alternative design places an active repeater, for boosting signal levels, between the star and tee.
- The star-star system shown in Fig. 9-11 illustrates the use of a repeater.

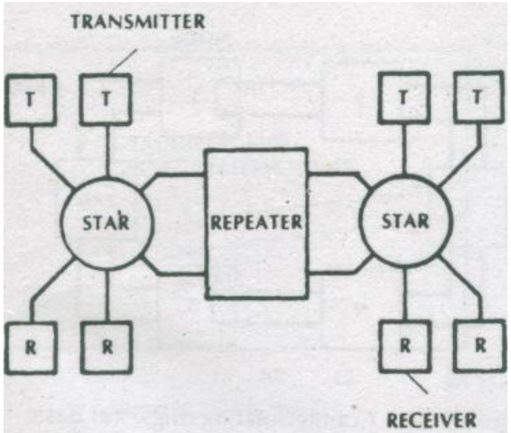


Figure 9-11 Star-star network.

Multi-fiber Systems

- TV-terminal systems can be implemented by directly connecting each terminal to all the others in the manner suggested by Fig. 9-12.
- At each transmitter, a single source illuminates a fiber bundle containing *N* - 1 fibers.
- To obtain the greatest efficiency, the source area equals that of the fiber bundle.
- Each fiber leads to one of the remote receivers. At the receiver, one fiber arrives from each of the distant transmitters.
- A fiber bundle illuminates the photodetector, whose active surface must be at least as large as the bundle.

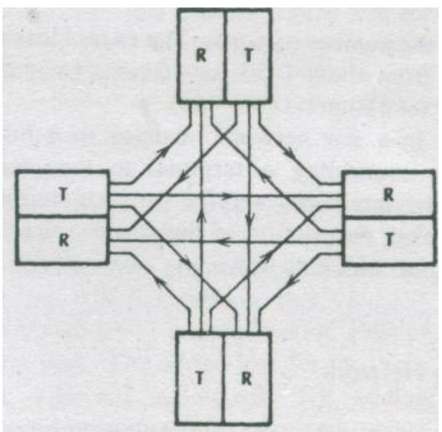


Figure 9-12 Multifiber bundle network.

- Although this architecture uses a lot of fiber, it does have **some advantages**.
- **First**, large-area emitters (which provide more total power than the small-area emitters required to excite small fibers) can be used.
- **Second**, the power launched into a fiber does not suffer attenuation from connectors or distribution couplers, as in tee or star systems.
- The transmission loss between terminals will be lower than in the tee or star. Some of the fibers can be eliminated if transmission is not required between every terminal.
- Although not particularly sophisticated, the multifiber network is still more economical than providing separate point-to-point links between every terminal.
- That scheme requires *(N* - 1) transmitters and *N* - 1 receivers at each terminal, for a total of *N(N* - 1) transmitters and *N(N* - 1) receivers.
- For example, a four-terminal point-to-point system requires 12 transmitters and 12 receivers. The multifiber bundle network needs only four transmitters and four receivers.

9-2 DIRECTIONAL COUPLERS

In this section we describe the design of several four-port directional couplers. Each uses a different concept to achieve the desired coupling.

- The **fused biconically tapered** directional coupler, sketched in Fig. 9-13, has been designed to provide low-loss couplers with a range of splitting ratios.
- The construction is fairly simple. Two single-mode or multimode fibers are twisted around one another and put under tension.
- The junction is heated, softening the fibers and causing their claddings to fuse.
- Pulling on the softened fibers forms a biconical taper at each of the four ports.

- In multimode fibers, coupling occurs because higher-ordered modes no longer strike the core-cladding interface beyond the critical angle in the tapered regions.
- As Fig. 9-13 illustrates, these modes are trapped by total reflection at the outer surface of the cladding. They have been converted into cladding modes.
- Rays from lower-ordered modes do not travel near the critical angle and will not be converted so easily.
- Power associated with these modes remains in the original fiber.
- Because the fused waveguides in Fig. 9-13 share the same cladding, power from higher-ordered input modes is now common to both fibers.
- The output tapers convert the cladding modes back into core-guided waves.
- The splitting ratio depends on the length of the taper and the cladding thickness.

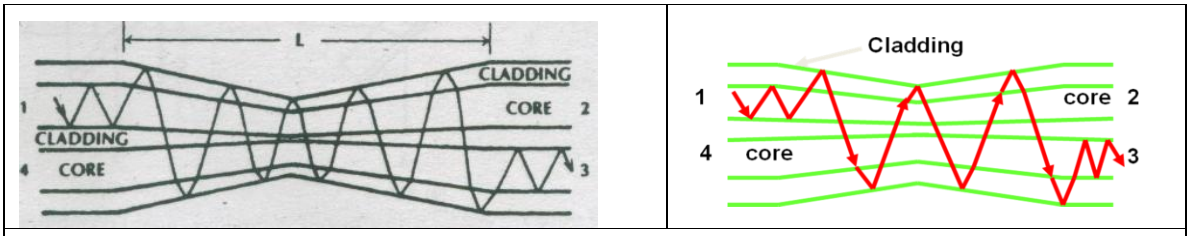


Fig 9-13 Fused biconically tapered directional coupler

- Single-mode operation of the tapered-and-fused coupler is explained by the exchange of energy in the overlapping evanescent fields associated with the two fibers.
- The taper brings the two cores closer to each other. The taper also decreases the fiber core diameter, thus lowering the normalized frequency (the *V* parameter).

- Referring to Fig. 5-19, we see that decreasing the *V* parameter increases the mode spot size. The increased spot size and diminished core separation enhance the overlap of the evanescent fields, improving the coupling.
- Another single-mode directional coupler is constructed by polishing much of the cladding from one side of a short section of each fiber and then butting the two polished surfaces together.
- The cores must be within several micrometers for good coupling in this, arrangement. As is the case with the tapered coupler, this device depends upon evanescent coupling for its success.
- The tapered (or polished) single-mode coupler is of such importance that a little more should be said about its operation. By using Fig. 9-1 as a reference for the ports and assuming an input at port 1, the coupling to ports 2 and 3 are given by

$$P_2/P_1 = \cos^2(\Delta\beta L)$$
$$P_3/P_1 = \sin^2(\Delta\beta L) \qquad (9\text{-}11)$$

where A/3 is the *coupling coefficient* (given in radians per meter) between the two waveguides and L is the length of fiber over which interaction exists. As seen from these equations, the input power divides between the two output ports with no loss. In a good practical coupler, the excess loss may be only a few tenths of a dB. As seen from the preceding equations, all the power appears at port 3 when the length of the interaction region is

$$L_c = \pi/2\Delta\beta \qquad (9\text{-}12)$$

The resulting length is called the *coupling length.* Figure 9-14 is a plot of the coupled power as a function of the length of the interaction region. Note that any desired splitting ratio can be obtained by suitably adjusting the length of the interaction region. Also notice that the fractional coupling repeats itself as the interaction length increases.

An offset butt joint can be used to form a four-port directional coupler in the manner illustrated in Fig. 9-15.[4] With an input at port i, the favored port (port 2 in the figure) collects an amount of power determined by the offset. The lateral-misalignment curve (Fig. 8-3) predicts the offset coupling loss for SI fibers.

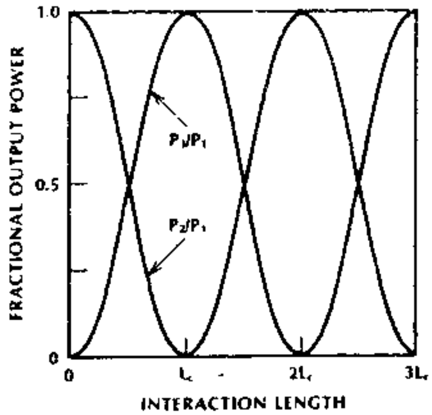


Figure 9-14 Fractional coupled power as a function of the length of the coupling region.

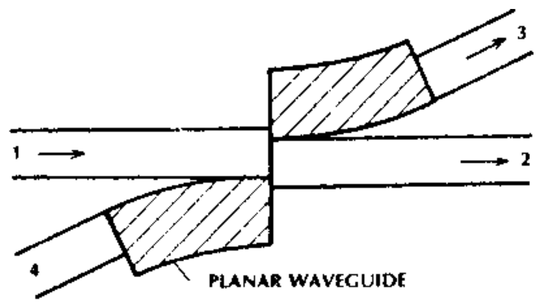


Figure 9-15 Offset butt-joint directional coupler. Power couples between the trunk fibers (1 and 2) and the tap fibers (3 and 4) by way of planar dielectric waveguides.

A portion of the incident light travels from the joint to the tap (port 3) along a planar curved plastic waveguide. The waveguide, and grooves for accurately positioning the fibers, en., be produced by a thick-film photolithographic process.

For conventional optic systems, a *beamsplitter* (partial reflector) serves as a simple directional coupler. A *beamsplitting plate,* pictured in Fig. 9-16(^. consists of a thin partially reflective coating (either dielectric or metallic) on a transparent substrate. The thickness and composition of the coating determine the splitting ratio. The beamsplitting plate displaces the transmitted beam laterally with respect to the incident beam. The *beam-splitting cube,* shown in Fig. 9-16(b), removes the displacement.

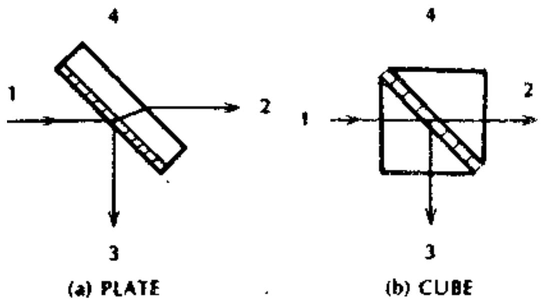


Figure 9-16 Beamsplitting directional couplers.

The cube consists of two prisms separated by a partially reflective coating.

A beamsplitter cannot be used by itself when dividing power among fibers. .The space occupied by the splitter is equivalent to a gap. As discussed in Section 8-1, gaps between connecting fibers produce large losses, because the diverging rays emitted by the input fiber miss the receiving fiber. Collimating the rays incident on the beamsplitter and refocus-ing the divided light onto the receiving fibers solves this problem. Figure 9-17 illustrates a beamsplitter-type directional coupler by using GRIN rod lenses for collimating and refocus-ing.[5] The beamsplitting cube aligns ports 1 and 2 (and ports 3 and 4). These ports would be offset if a beamsplitting plate were used. The coupler in Fig. 9-17 would also work if conventional spherical lenses replaced the GRIN lenses.

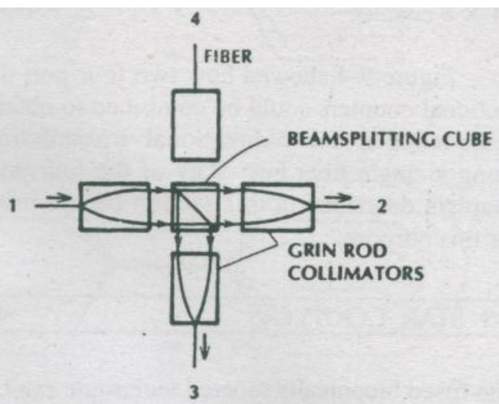


Figure 9-17 Directional coupler using four GRIN rod collimating lenses attached to the fibers.

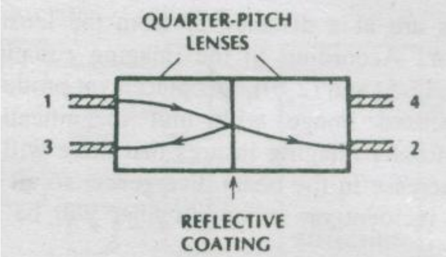


Figure 9-18 Directional coupler.

A variation of the beamsplitting coupler appears in Fig. 9-18. Two quarter-pitch GRIN rod lenses, separated by a partially reflective coating, make up the coupler. The connecting fibers are offset from the axes of the lenses. Consider an input at port 1. The combined lenses image light from port 1 onto the fiber at port 2. Ilight reflected by coating is imaged onto port 3. None of the light reaches port 4. Inputs at the other ports are similarly distributed.

Beamsplitting couplers are ***amplitude-division*** devices. They distribute light by dividing the amplitude of the incident wave into the desired proportions. Couplers can also be produced by wave*front division,* dividing the wavefront into several parts and directing the separated waves to the desired ports. Figure 9-19 illustrates a coupler operating on this principle. The input light, from port 1, diverges. The upper half of the wave is imaged onto the fiber at port 2 by concave reflector *M*,. The lower half of the wave is imaged onto the fiber at port *3* by concave reflector M2. As drawn, the splitting ratio is 1:1. Other ratios are obtained by enlarging one of the reflectors, so that it intercepts more of the wavefront than the other reflector.

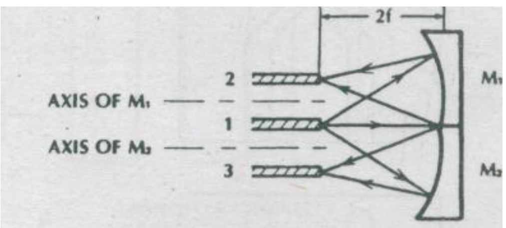


Figure 9-19 Wavefront-dividing directional coupler.

The fibers in Fig. 9-19 are placed near the center of curvature and slightly off the axis of each reflector. A spherical reflector's focal length f is half its radius of curvature, so the fibers are at a distance 2/ from the lenslike mirror. According to the imaging equations Eqs. (2-5) and (2-6)], this placement produces a focused image with unit magnification. One-to-one imaging insures that there will be no increase in the beam divergence, so all the light incident on an output fiber will be accepted.

An input at port 2 of the wavefront-dividing device couples only to port 1.

Similarly, an input at port 3 couples only to port 1. The coupler in Fig. 9-19 has just three ports. A duplexing system (see Fig. 9-2) only requires three-port couplers. Connecting two three-port couplers, as in Fig. 9-20, produces a four-port directional coupler if needed.

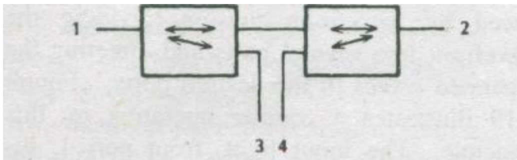


Figure 9-20 Connecting two three-port couplers to obtain a four-port directional coupler.

Couplers can also be fabricated in the integrated optic format. In one such implementation, waveguides are diffused into a glass substrate by using ion-exchange techniques. These waveguides are circular, as indicated in Fig. 9-21, conforming to the structure of optical fibers.

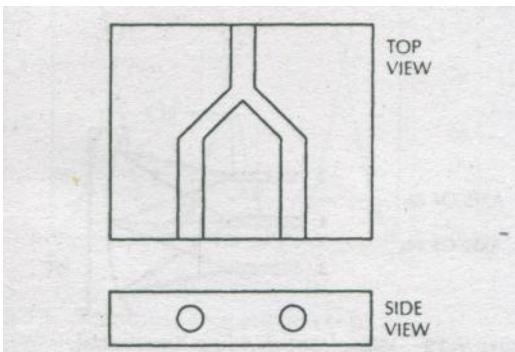


Figure 9-21 Integrated optic branching coupler.

This configuration simplifies the connection of these couplers to the rest of the fiber system. Core sizes and numerical apertures are made to match those of the fibers to which the couplers will be attached. Both single-mode and multimode couplers have been constructed. For example, core sizes in the couplers are approximately 9, 50, or 62.5 /xm to match the most widely used single-mode and graded-index multimode fibers.

The coupling is formed by branching the imbedded waveguides in a Y junction as illustrated in Fig. 9-2*1.* One-by-two (1X2) couplers are the basic building blocks of this structure, but many more terminals can be connected by cascading several of them together. Figure 9-22 shows how a 1 X 8 coupler can be constructed by cascading several 1 X 2 couplers in a tree configuration.

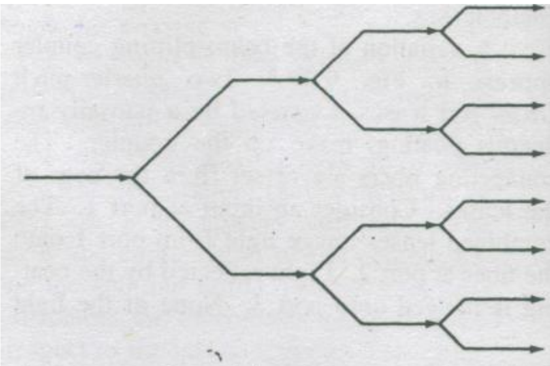


Figure 9-22 Cascaded 1 × 2 couplers to produce a 1 × 8 coupler.

Figure 9-4 showed how two four-port directional couplers could be combined to obtain a tee coupler for bidirectional transmission along a single fiber bus. Any of the four-port couplers described in this section can be used for this purpose.

9-3 STAR COUPLERS

- The fused biconically tapered technique can be extended to produce multimode fiber couplers having more than four ports. An 8 X 8 transmission *star coupler* and an eight-port *reflection star coupler* are illustrated in Fig. 9-23.
- Individual multimode fibers are wound around one another and fused while under tension.
- For the transmission star, power put into any port on one side of the coupler emerges from all the ports on the other side, divided equally. Ideally, ports on the same side of the coupler are isolated from each other.
- Figure 9-7 illustrates how the transmission star coupler interconnects terminals.

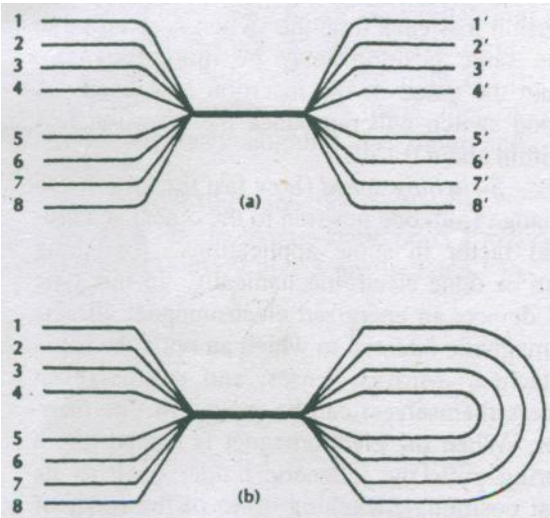


Figure 9-23 Star couplers. (a) Transmission star (b) Reflection star.

- The reflection star couples light from any one port to all the ports. It interconnects terminals as shown in Fig. 9-24. Because every fiber connected to the star carries both transmitted and received data, a directional coupler is needed to separate the two signals at each terminal.
- Fusion of more than two single-mode fibers to produce multiterminal star couplers does not work well because of the need to couple between the individual evanescent fields of the many fibers. For single-mode systems, star couplers are made by cascading 1X2 port fused couplers. The scheme, illustrated in Fig. 9-22, works for any type of coupler construction.

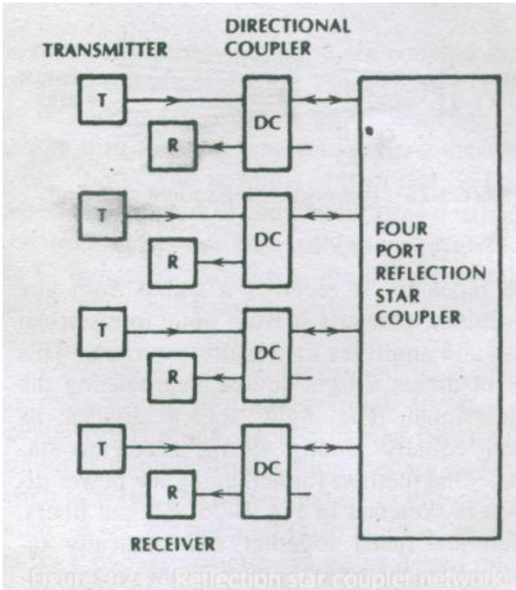


Figure 9-24 Reflection star coupler network.

- The star couplers just described are passive devices. They feature reliability and low cost compared with active devices. However, active stars can be very useful in implementing LANs.[10] A schematic of an active star network appears in Fig. 9-25. The active star acts as a repeater.

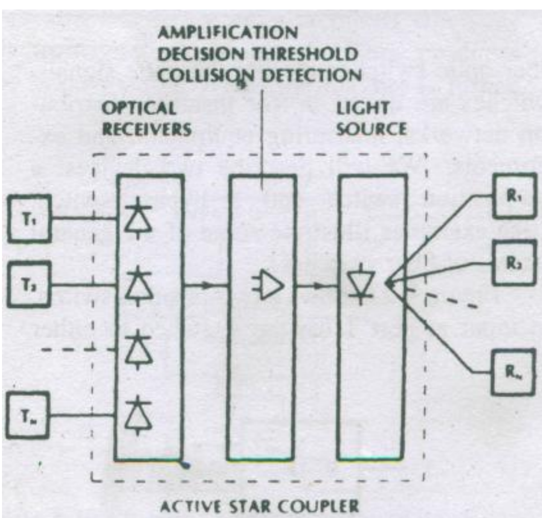


Figure 9-25 Active star network.

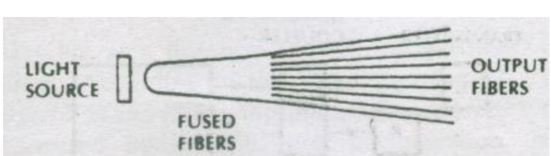


Figure 9-26 Power-dividing source coupling.

- It receives a signal from any transmitter, converts it from optic to electrical form, and amplifies the resulting current. This current drives a light source, reproducing the optic signal. The light source divides its power equally among all the receiving stations. One method for achieving the power division is sketched in Fig. 9-26, Output fibers, which are fused together and conically tapered, share the light emitted by the source.
- The active star can include provisions for detecting collisions between data packets transmitted simultaneously by different terminals. If collisions occur, then the repeater signals the stations to take corrective actions. Active stars add flexibility to a distribution network because of their regenerating and collision detecting properties.

9-4 SWITCHES

- Fiber optic switches **reroute** the optic signals.
- Switches are useful in, for instance, distribution networks, measuring equipment, and experiments.
- We will describe two devices:
  - a two-position switch and
  - a bypass switch.
- These examples illustrate some of the general features of fiber switches.

Figure 9-27 shows a **two-position** switch. An input at port 1 can be switched to either port 2 or port 3. For the following definitions, assume the switch is set for coupling to port 2.

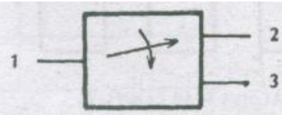


Figure 9-27 Two-position switch.

The insertion loss *(IL)* (in decibels) is

$$L_{IL} = -10 \log \frac{P_2}{P_1} \qquad (9\text{-}13)$$

- where P, is the power going into port 1 and P_2 is the power emerging from port 2.
- Insertion loss depends on fiber alignment, just like the loss of a simple connector. Losses of less than 1 .5 dB can be obtained with good mechanical switches.
- In addition to having low insertion loss, a good switch will have the same value of insertion loss for all switch positions.

- ***Crosstalk*** (CT) is a measure of how well the uncoupled port is **isolated**. It is given by

$$L_{CT} = -10 \log \frac{P_3}{P_1} \qquad (9\text{-}14)$$

- where P_3 is the power emerging from port 3.
- Crosstalk depends on the particular design of the switch, but values of 40-60 dB are typical.
- ***Reproducibility*** (achieving the same insertion loss each time the switch is returned to the same position) may be more important than the value of the

insertion loss itself. A good switch will reproduce the insertion loss within about 0.1 dB.

- ***Switching speed*** (how fast the switch can change from one position to the other) is a crucial factor in some applications.
- Switching can be done electromechanically.
- In this type of device, an energized electromagnet attracts a magnetic material to which an optic device is attached.
- Mirrors, lenses, and prisms (even fibers themselves) can be moved in this manner.
- When the electromagnet is turned off, a spring pulls the magnetic holder back to its rest position.
- Switching times of the order of a **few milliseconds** can be obtained with electromechanical switches.

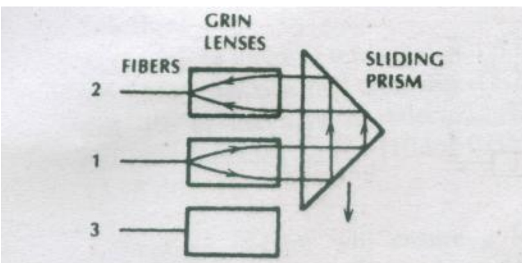


Figure 9-28 Sliding-prism, two-position switch.

- The two-position switch drawn in Fig. 9-28 consists of a **sliding prism** and quarter-pitch lenses attached to each fiber.
- In the position shown, light couples between ports 1 and 2. Let us follow the progress of an input at port 1. A GRIN lens collimates the diverging beam emitted by the fiber. The right-angled prism deflects the light by total internal reflection at its two slanting surfaces. A GRIN lens refocuses the collimated beam onto fiber 2. To direct light from port 1 to port 3, the prism moves in the direction shown in the figure, aligning the beam between fibers 1 and 3. Collimating lenses are required to eliminate insertion loss caused by beam spreading and to ensure that all rays strike the prism's reflecting surfaces beyond the critical angle. The right-angled prism not only reflects the light but it translates the beam parallel to itself, thereby effectively angularly aligning the input and output fibers.

- Figure 9-29 illustrates the functions of a **bypass switch**. In the bypass state, ports 1 and 4 are coupled; ports 2 and 3 are isolated.

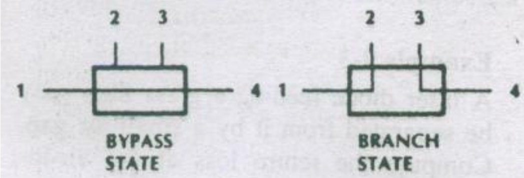


Figure 9-29 Bypass switch.

- In the **branch state**, ports 1 and 2 are coupled and ports 3 and 4 are coupled.
- The bypass switch can be incorporated into a **tee network** by attaching it to the data bus in the way indicated in Fig. 9-30.
- The terminal shown can be bypassed or included in the network, as desired. A station that is not transmitting or receiving can be bypassed.
- Similarly, the bypass switch can be used to bypass a node in a ring network.

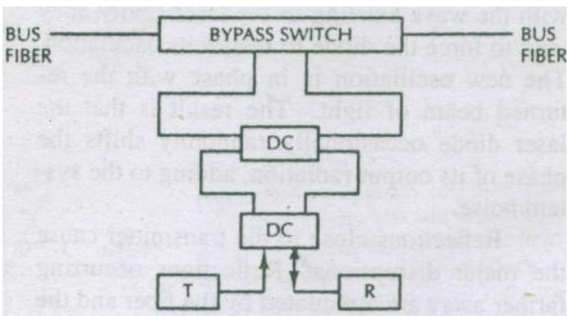


Figure 9-30 Bypass switch incorporated into a tap for a tee network.

- A repeater can be connected to a data bus, replacing the terminal in Fig. 9-30.
- If the repeater needs repair, then it can be bypassed without shutting down the entire network.
- The switch provides a fail-safe feature in this application.
- A second repeater (also attached to the bus by a bypass switch) can be switched into the network, taking the place of the malfunctioning repeater.
- This strategy, using redundancy, improves the network reliability at the expense of increased system complexity.

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9-5 FIBER OPTICAL ISOLATOR

- Laser diodes are particularly sensitive to light energy reflected back from the rest of the system. The reflected light increases the noise in the emitted beam, degrading system performance.
- The returning photons arrive back inside the laser cavity where they are amplified and generally take part in laser action. They compete with the photons already in the cavity for the excited atomic states.
- Because the returning photons are unlikely to be in phase with the wave existing in the laser cavity, they tend to force the diode to restart its oscillation.
- The new oscillation is in phase with the returned beam of light. The result is that the laser diode occasionally randomly shifts the phase of its output radiation, adding to the system noise.

- Reflections close to the transmitter cause the major disruptions. Reflections occurring farther away are attenuated by the fiber and the connectors (and any other components in the path), becoming small when arriving back at the laser diode.
- Thus, most of the precautions to be mentioned here apply only to portions of the system located near the transmitter.
- **Reflections are minimized in a number of ways in practical systems.**
- Components, such as the fiber or any lenses in the system, can have their ends anti-reflection coated to reduce the amplitude of any return.
- Fiber ends can be rounded so that reflected rays do not propagate back to the transmitter but are diverted out of range of the allowed propagating modes.
- Connectors and couplers are specifically designed to minimize the amount of reflected light. The measure of effectiveness in controlling reflections is the *return loss.*
- Expressed in decibels, it is defined as

I* = -10 log £ (9-15)

where *P,* is the power incident on the component and P_r is the power reflected. Return losses of 30 or 40 dB are representative of well-designed components, but 50 or even 60 dB are sometimes required.

Figure 9-34 Isolator operating in the forward direction.

9-6 WAVELENGTH-DIVISION MULTIPLEXING

- Optic beams with different wavelengths propagate without interfering with one another, so several channels of information (each having a different carrier wavelength) can be transmitted simultaneously over a single fiber.
- This scheme, called *wavelength-division multiplexing* (WDM), increases the information-carrying capacity of a fiber.
- In Chapters 3, 4, and 5 we determined the capacity limits due to material and waveguide dispersion and modal distortion.
- These limits apply to the information carried at any one wavelength. Increasing the number of carriers increases the capacity proportionately.
- An *optic multiplexer* couples light from the individual sources to the transmitting fiber, as shown in Fig. 9-35.
- At the receiving station an *optic demultiplexer* separates the different carriers before photo-detection of the individual signals (see Fig. 9-35).
- Generally, multiplexers/demultiplexers have fibers at their input and output ports.
- It is also possible to replace the input fibers in a multiplexer with optic sources directly integrated into the device.
- Similarly, photodetectors can replace the output fibers in a demultiplexer. Often the same device can perform as a multiplexer or demultiplexer.

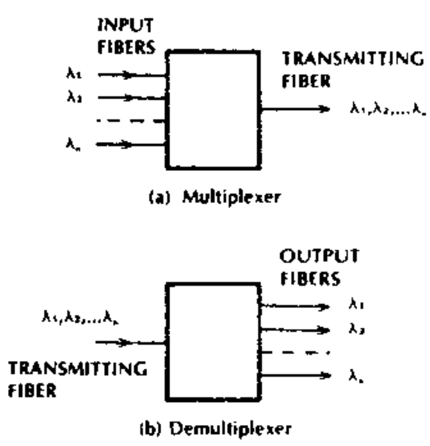

Figure 9-35 Schematic of (a) an optical multiplexer and (b) an optical demultiplexer.

- Insertion loss and crosstalk are the important properties of multiplexers/demultiplexers.

- The multiplexer operates in the third window, where fiber losses are low and where the erbium-doped amplifier works so well.
- Because of this, WDM systems are popular for high-capacity, long transmission paths, such as those encountered in undersea links.
- Multiplexers have been designed to accommodate numerous channels (more than 100 have been reported), with bandwidths and spacings under 1 nm. When there are more than just a few (2 or 3) WDM channels, the system is referred to as *dense wavelength-division multiplexing.*
- Figure 9-37 illustrates a three-channel WDM system. In its simplest form this network is unidirectional.
- It can, however, operate in both directions if the wavelength-separation devices are bidirectional. Later in this section we will see how such devices can be constructed. When operating bidirectionally, directional couplers must be included at each terminal to separate the transmitted and received waves.

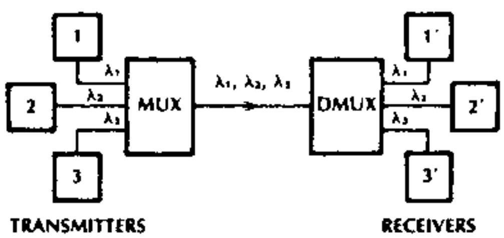

Figure 9-37 Three-channel wavelength-division-multiplexed network. MUX, multiplexer; DMUX, demultiplexer.

- Previously installed systems, designed to operate with a single carrier, can be upgraded by WDM. Only the terminal equipment need be changed. The original fibers can remain in place.

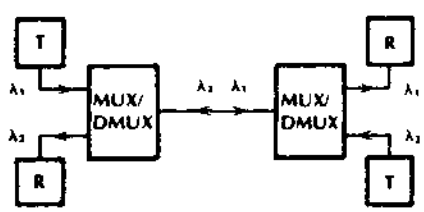

Figure 9-38 Full-duplex network. T, transmitter; R, receiver; MUX/DMUX, bidirectional multiplexer.

Several multiplexer designs are based on either of two mechanisms: angular dispersion or optic filtering. Two devices exhibiting angular dispersion are the prism and the reflecting diffraction grating. Figure 9-39 shows how these bidirectional elements separate (or combine) beams of different wavelengths. The grating may be metal coated to enhance its reflectance. Optic filters (drawn in Fig. 9-40) consist of thin layers of transparent materials of different refractive indices. Interference within the thin films causes the filter to pass certain wavelengths and reflect others. In the scheme shown in the figure two filters in series separate (or combine) three wavelengths.

Multiplexers / demultiplexers often incorporate lenses to capture the diverging rays emitted by the input fiber, to direct these rays onto the combining/separating elements, and to refocus the light onto the output fiber. Without the lenses, the gap loss between the input and output fiber would be excessive. Lenses perform another needed function. They collimate the beam striking the wavelength-selective element. This is necessary because angularly dispersive components and optic filters are sensitive to the angle of incidence. Diverging incident rays would also diverge at the output of the selective element, each wavelength occupying a range of angles. This in turn would decrease the possibility of spatially separating the individual wavelengths present.

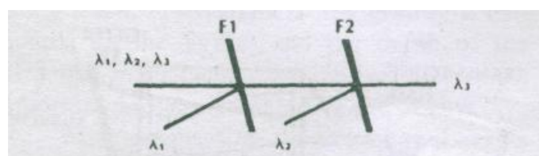

Figure 9-40 Optical filtering. Filter F1 reflects λ_1 and transmits λ_2 and λ_3, and filter F2 reflects λ_2 and transmits λ_3.

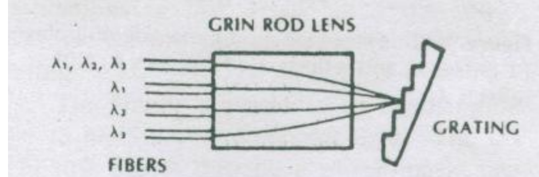

Figure 9-41 Crating multiplexer/demultiplexer. Only the fiber's axial rays are drawn.

To illustrate some of the available construction techniques, two multiplexers will be described. First consider the grating multiplexer drawn in Fig. 9-41. For simplicity only the central rays associated with each fiber are shown. However, the beams leaving any fiber are diverging and the beams entering any fiber are converging. The beams are collimated in the space between the lens and the grating. The upper fiber is the system's transmission line. When used as a demultiplexer, wavelengths A,, A_2, and A_3 enter the quarter-pitch GRIN rod lens from the transmission line. The lens collimates the beam before the rays strike the grating. The grating spatially separates the three wavelengths, after which the lens focuses the angularly displaced colli-mated beams onto the three output fibers. This device is bidirectional. When used as a multiplexer, the direction of ray travel is reversed. Inputs at the lower three fibers are combined by the grating and focused onto the transmission line (the upper fiber).

The second multiplexer, drawn in Fig. 9-42, uses a GRIN rod lens and optic filters.[15] Filter Fl passes wavelength Aj and reflects A_2

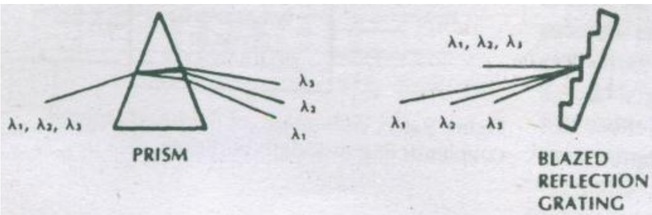

Figure 9-39 Angular dispersion.