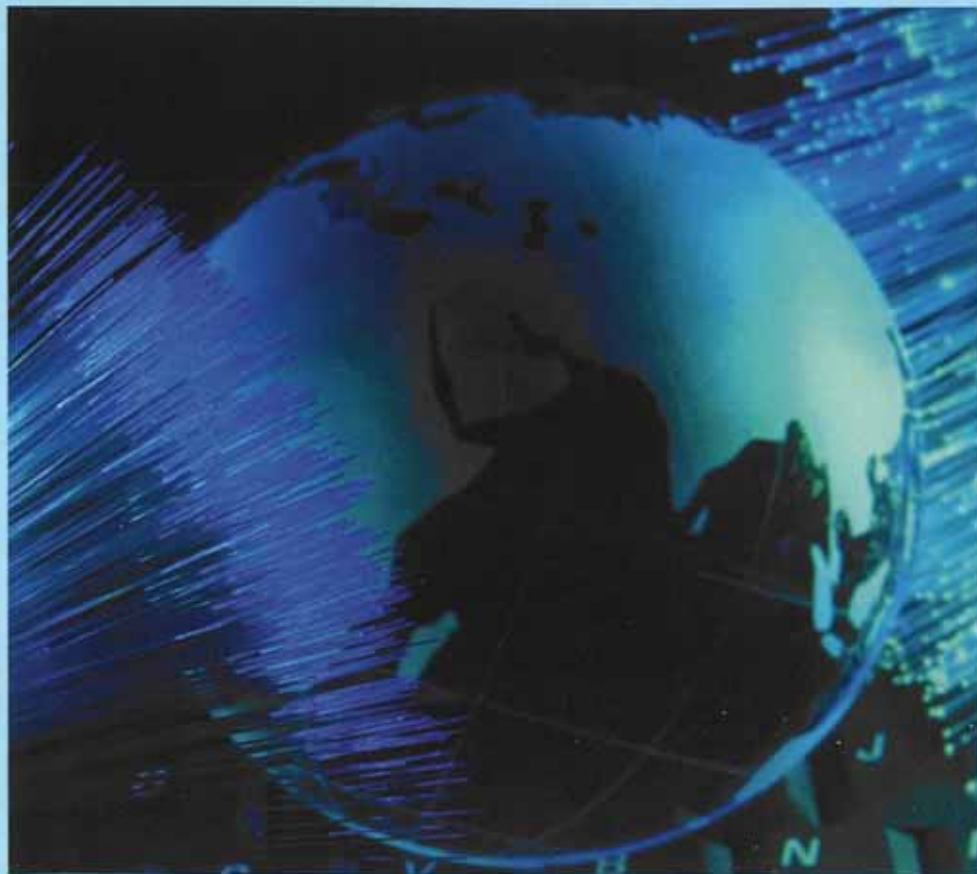


Understanding Fiber Optics

5th edition

Jeff Hecht



Laser Light Press

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Fifth edition, revised

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broadcasts signals at a specific frequency or band. Stations are set at standard frequencies, such as 89.7 MHz for an FM radio station or 204 to 210 MHz assigned to channel 12 on the U.S. television dial. Other broadcasters in the region are assigned other frequencies. You tune your radio or television receiver to select one of these frequencies, but all of them are transmitted through the air simultaneously. (For broadcasting, a buffer is usually kept in reserve between adjacent channels, so neither channel 11 nor channel 13 would operate in the same area as channel 12.) Broadcast signals go through the air, but frequency-division multiplexing also works through cable. In fact, frequency-division multiplexing is standard in cable television, where certain frequency bands are reserved for specific video channels, although the frequencies may not match those on the broadcast dial.

- *Wavelength-division multiplexing* is the optical counterpart of frequency-division multiplexing. Separate signals modulate light sources emitting at different wavelengths, just as separate signals modulate radio transmitters broadcasting at different frequencies. Each separate wavelength is an *optical channel*. Light from the separate sources is combined and transmitted through a single optical fiber. Then the wavelengths are separated again, or *demultiplexed*, at the other end, as shown in Figure 3.3. As with frequency-division multiplexing, the wavelengths can be packed closely together, but the signals must not overlap.

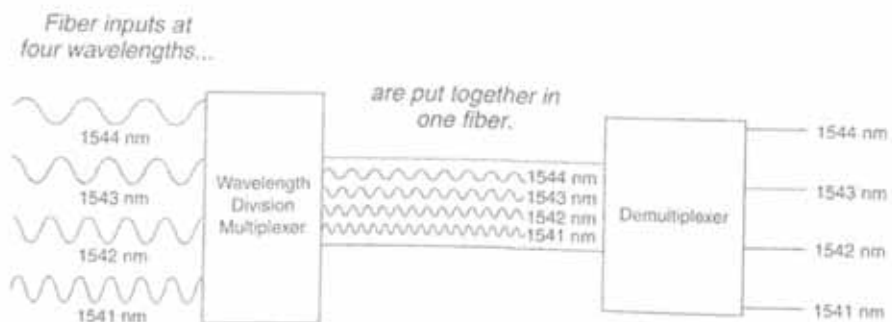
- *Time-division multiplexing* combines streams of bits from two or more sources to produce a single stream of bits at a faster rate, as shown in Figure 3.4. For example, four signals at 10 million bits (megabits) per second can be combined to generate one 40-Mbit/s signal. Figure 3.4 shows data bits being interleaved, with one bit from stream A followed by one from stream B, then one from stream C, one from stream D, and finally the next bit from stream A. As you will learn later, other variations on time-division multiplexing may arrange the incoming data bits differently, such as in blocks called *packets*. Note that time-division multiplexing is designed specifically to work with digital signals made of strings of incoming bits.

Note that although demultiplexing may seem to be merely the opposite of multiplexing, separating the combined signals often is a more complex and demanding task than

Time-division multiplexing works only for digital signals.

FIGURE 3.3

Wavelength-division multiplexing combines signals in one fiber.



Electronic time-division multiplexing becomes extremely difficult at higher data rates. An alternative is *optical time-division multiplexing*. Interleaved optical TDM has been demonstrated in the laboratory, but applications are far off.

Frequency-Division Multiplexing

Frequency-division multiplexing combines two or more signals modulated on carriers at different frequencies to produce one signal covering a range of frequencies. This system is used in broadcast radio and television and in cable television. Traditionally frequency-division multiplexing is used for analog signals, but it also can be used for digital signals.

Frequency-division multiplexing divides a range of frequencies into a set of distinct channels with fixed bandwidths that do not overlap. Each input signal modulates the carrier frequency for one channel, producing a signal that fits into one channel slot. Combining the modulated carriers produces a signal that spreads across a wider range of frequencies. You can see this on an AM or FM radio dial, where each station has a nominal frequency (the carrier) that actually spreads across a wider range, but should not overlap with the signals of other stations. The radio band contains dozens of stations; you tune your receiver to select a specific station. Television works the same way, but the channels are numbered rather than named by frequency, and some frequencies are reserved for services other than television.

Cable television also uses frequency-division multiplexing, but transmits the combined signals through optical fiber and coaxial cable rather than broadcasting them. Like broadcast television, cable systems assign channel numbers, which identify assigned frequencies. The different channels may carry different types of signals, including analog video, digital video, voice, and data.

Like time-division multiplexing, frequency-division multiplexing is done electronically before the signal reaches the transmitter. In practice, the term *frequency-division* is limited to multiplexing at radio frequencies.

Wavelength-Division Multiplexing

Think of wavelength-division multiplexing as being the optical version of frequency-division multiplexing. It transmits multiple optical signals through the same optical fiber at different wavelengths, just as frequency-division multiplexing transmits multiple radio signals at different frequencies. The basic principles are the same, but the terminology and details are different.

In practice, one optical transmitter is assigned per wavelength, as shown in Figure 10.4. The input is (generally) a digital signal from an electronic multiplexer. The optical transmitter modulates that signal onto the output of a light source at a wavelength λ . Other signals modulate the outputs of other transmitters with light sources at other wavelengths.

Separate fibers deliver the output of each transmitter to an optical multiplexer, which combines them for transmission through a single output fiber. Each wavelength in the signal is a separate optical channel, which if the system is designed properly does not affect other optical channels, as in frequency-division multiplexing of radio broadcast through the air.

Frequency-division multiplexing combines signals at different frequencies.

Wavelength-division multiplexing is the optical version of frequency-division multiplexing.

and moisture. They are designed to operate even after having one end stuck in mud and wiped out with a rag! Normally, nonmilitary users will avoid outdoor connectors or house them in enclosures that are sealed against dirt and moisture.

Connector Structures

A wide variety of fiber-optic connectors have been developed, but the number of basic design approaches is more limited. The two most common approaches differ in how they align the fibers: One mounts the fibers in a cylindrical ferrule, the other aligns them in V-shaped grooves in a flat substrate. A third approach with limited applications expands the beam from the fiber to reduce sensitivity to mechanical tolerances.

Ferrule-Based Connectors

The common elements of ferrule-based connectors are shown in generic form in Figure 13.7. The fiber is mounted in a long, thin cylinder called a *ferrule*, with a hole sized to match the fiber cladding diameter. The ferrule centers and aligns the fiber and protects it from mechanical damage. The fiber end is at the end of the ferrule, where it can be polished smooth. The ferrule is mounted in a connector body, which is attached to the cable structure. A strain-relief boot protects the junction of the connector body and the cable.

Ferrules are typically made of metal or ceramic, but some are made of plastic. The protective plastic coating is stripped from the fiber before it is inserted in the ferrule. The hole through the ferrule must be large enough to fit the clad fiber and tight enough to hold it in a fixed position. Standard bore diameters are $126 \pm 1/-0 \mu\text{m}$ for single-mode connectors and $127 \pm 2/-0 \mu\text{m}$ for multimode connectors, but some manufacturers supply a range of sizes (e.g., 124, 125, 126, and 127 μm) to accommodate the natural variation in fiber diameter. Adhesive is typically put in the hole before the fiber is pushed in to hold the fiber in place. The fiber end may be pushed slightly past the end of the ferrule and then polished to a smooth face.

Ferrules center and align the fiber in the connector.

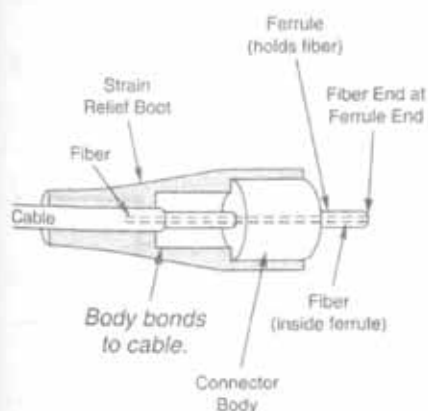


FIGURE 13.7

A simplified generic ferrule fiber connector.

The ferrule may be slipped inside another hollow cylinder (also called a sleeve) before it is mounted in the connector body. The body, typically made of metal or plastic, includes one or more pieces that are assembled to hold the cable and fiber in place. Details of assembly vary among connectors; cable bonding is usually to strength members and the jacket. The end of the ferrule protrudes beyond the connector body to slip into the mating receptacle. A strain-relief boot is slipped over the cable end of the connector to protect the cable-connector junction.

Special ferrule connectors are used for operation at high powers. Heat from light absorption at the junction can damage standard epoxies and fiber coating materials, so the coatings must be removed (they often are anyway) and special high-temperature epoxies must be used. Quartz sleeves may be added to protect the fiber tip, especially at higher powers.

V-Groove Connectors

V-groove connectors can align fibers in connectors.

V-groove connectors avoid the need for a ferrule by aligning two fiber ends in a V-groove structure. One approach is by pressing a free fiber down into a groove and butting it up against another fiber already installed in the groove. An alternative is to align fibers in V grooves in a substrate, fix them in place, then mate two V-grooved elements together. If the grooves are accurately spaced, the fiber ends match accurately, just as ferrules do. In a sense, the grooved material serves the same function as a ferrule.

V-groove structures are easily adaptable for multifiber connectors by etching multiple grooves in each element to align them to mate the fibers they contain end-to-end. Guide pins can be added to the V-groove elements to mate them accurately.

Expanded-Beam Connectors

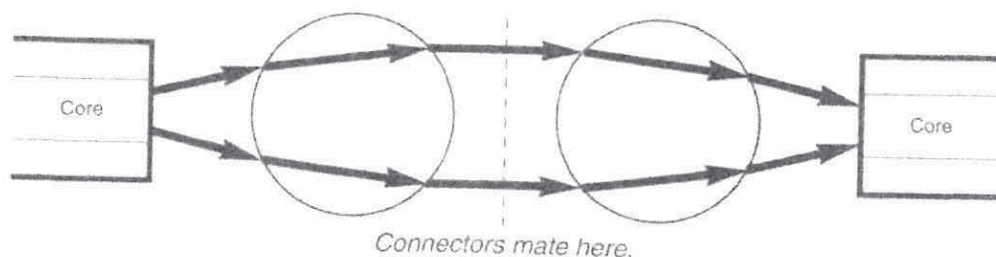
Military field cables often use expanded-beam connectors.

Expanded-beam connectors are limited to applications where large tolerances are required, such as military field cables. As shown in Figure 13.8, light diverging as it exits the input fiber passes through a spherical lens, which collimates the light rays so they are parallel. Then a spherical lens attached to the output cable focuses the light rays into the output fiber.

This expands the beam diameter by a factor of 10 or more for multimode fiber, and by a larger factor for single-mode fiber, spreading the optical signal over a larger region. This design prevents dirt from blocking all or most of the beam, or small misalignments from causing high attenuation. In practice, expanded-beam connectors are mostly for cables used outdoors or in hostile environments where connectors can't be protected.

FIGURE 13.8

Operation of an expanded-beam connector.



Statistical multiplexing requires a set of priorities because too many packets may queue up while waiting to be transmitted. One approach is to allow packets to "time out" after a certain interval, like a person who gives up after waiting on hold for customer service. This method is used in the traditional version of the Internet Protocol (IPv4). A refinement is to set higher priority for delay-sensitive traffic, such as telephone conversations or streaming video, so it goes to the head of the transmission queue, while lower-priority data packets wait; this is used in IPv6, which is not yet implemented across the entire Internet.

Wavelength-Division Multiplexing

Wavelength-division multiplexing (WDM) is the transmission of different signals on multiple wavelengths through the same fiber. It closely resembles electronic frequency-division multiplexing, but is done at the much higher frequencies of light waves, as shown in Figure 19.14. The optical channels at 193.1, 193.2, 193.3, and 193.4 THz are the optical counterparts of the radio-frequency channels at 174, 180, 186, and 192 MHz shown in Figure 19.13.

Channel spacing may be defined in terms of frequency or wavelength, but if the carriers are in the optical or infrared part of the spectrum, the process is generally called wavelength-division multiplexing. Standards have been set for two types: *dense-WDM* (DWDM) and *coarse-WDM* (CWDM).

Dense-WDM packs signals closely together, usually for long-distance transmission, and usually in the *erbium-amplifier band* between about 1530 and 1610 nm. Standards specify DWDM spacings in frequency units as 50, 100, and 200 GHz, which correspond to about 0.4, 0.8, and 1.6 nm in wavelength units near 1550 nm. The same standards also allow for spacing at 400 and 1000 GHz, which usually are not considered DWDM. The packing density of DWDM systems is limited by the modulation bandwidth of the signals, so 2.5-Gbit/s signals can be packed more tightly together than can 10-Gbit/s signals.

WDM transmits signals at multiple wavelengths through one fiber.

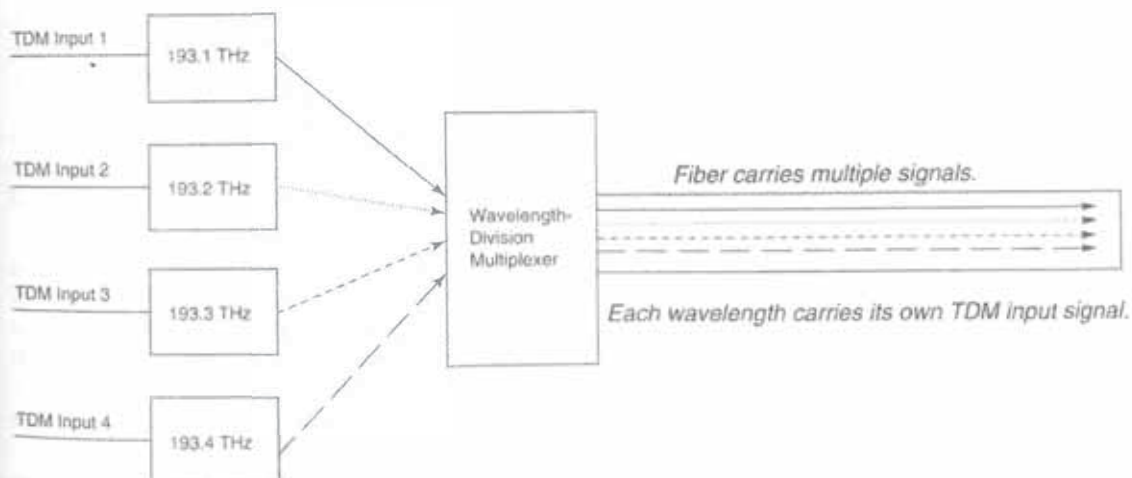


FIGURE 19.14

Wavelength-division multiplexing.

Electro-Absorption Modulator A semiconductor diode reverse-modulated so it modulates light passing through it.

Electromagnetic Interference (EMI) Noise generated when stray electromagnetic fields induce currents in electrical conductors.

Electromagnetic Radiation Waves made up of oscillating electrical and magnetic fields perpendicular to one another and traveling at the speed of light. Can also be viewed as photons or quanta of energy. Electromagnetic radiation includes radio waves, microwaves, infrared, visible light, ultraviolet radiation, X rays, and gamma rays.

EMI See *Electromagnetic Interference*.

Endoscope A fiber-optic bundle used for imaging and viewing inside the human body.

Erbium Band The range of wavelengths where erbium-doped fiber amplifiers are used, from 1530 to 1610 nm.

Erbium-Doped Fiber Amplifier (EDFA) Optical fiber doped with the rare earth element erbium, which can amplify light at 1530 to 1610 nm when pumped by an external light source.

Ethernet A local-area network standard. The original Ethernet transmits 10 Mbit/s. Other versions are Fast Ethernet at 100 Mbit/s, Gigabit Ethernet at 1 Gbit/s, and 10-Gigabit Ethernet.

Evanescent Wave Guided light waves that extend beyond the boundary of a fiber core into the cladding. Evanescent waves can transfer energy between waveguides.

Excess Loss Loss of a passive coupler above that inherent in dividing light among the output ports.

External Modulation Modulation of output of a light source by an external device.

Extrinsic Loss Splice losses arising from the splicing process itself.

Eye Pattern A pattern formed by overlaying traces of a series of transmitted pulses in a visual display.

The more open the eye, the sharper the distinction between on and off pulses.

Fabry-Perot A resonant cavity formed by a pair of mirrors aligned parallel to each other. A Fabry-Perot laser is a diode laser with its edge facets cleaved so they form a Fabry-Perot cavity.

Ferrule A tube within a connector with a central hole that contains and aligns a fiber.

Fiber Amplifier An optical fiber doped to amplify light from an external source. The most important type is the erbium-doped fiber amplifier.

Fiber Bragg Grating An optical fiber in which the core refractive index varies periodically along its length, causing Bragg scattering at wavelengths selected by the period and refractive index. A fiber Bragg grating reflects the selected wavelength and transmits others.

Fiber Distributed Data Interface (FDDI) A standard for a 100-Mbit/s fiber-optic local-area network.

Fiber-Optic Gyroscope A coil of optical fiber that can detect rotation about its axis.

Fiber to the Curb (FTTC) Fiber-optic service to a node that is connected by wires to several nearby homes, typically on a block.

Fiber to the Home (FTTH) A network in which optical fibers bring signals all the way to homes.

Fiber to the Premises (FTTP) Distribution of signals through fiber optics all the way to individual residences. Functionally the same as fiber to the home.

Fibre Channel A standard for data transmission among storage devices and computers over fiber or copper.

FITL Fiber in the loop.

Fluoride Glasses Materials that have the amorphous structure of glass but are made of fluoride compounds (e.g., zirconium fluoride) rather than oxide compounds (e.g., silica).