CHAPTER 5.6

OPTICAL FIBER COMPONENTS

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INTRODUCTION

Optical fibers are thin (~100 μm diameter), normally cylindrical, strands of optically transparent material (usually glass or plastic) that are capable of guiding light over long distances with low loss. The basic principles by which optical fibers guide light were discovered in the nineteenth century, applied to the transmission of images in the first part of the twentieth century, and to telephony and data communications in the last part of the twentieth century.

Optical fiber communications systems provide many advantages over their predecessors, the greatest of which is their ability to transmit information at incredibly high rates. In laboratory demonstrations, rates of over 10 Tb/s, or the equivalent of roughly 150 million simultaneous telephone calls, have been achieved in a single fiber. In theory, much higher rates are possible. Optical fiber communications is the key enabling technology of the Internet.

Bundles of optical fibers with their relative positions fixed (imaging bundles) continue to be used to transmit images, and optical fibers have other applications in medicine, sensing, and illumination.

This section covers some of the most important properties of optical fiber and the components used with fiber, especially in communications systems.

Transparency

Glass, especially with very high silica content, can be highly transparent. Early optical fiber used for imaging bundles typically attenuated visible light by factors in the range of 0.1 dB/m (2.3 percent/m) to 1 dB/m (21 percent/m), low enough to permit useful transmission of images over distances of meters. Analyses performed in the 1960s indicated that much lower levels of attenuation could be achieved, perhaps lower than 10 dB/km, making it possible to consider the use of optical fiber as a communications medium over distances of kilometers. In the 1970s, these predictions were fulfilled, and levels of attenuation continued to be reduced until they now approach what is considered to be the fundamental limit in silica glass, approximately 0.15 dB/km at wavelengths near 1550 nm.

Attenuation mechanisms include intrinsic absorption, which in glass generally occurs in the ultraviolet and mid-infrared regions, absorption by impurities, losses associated with waveguide properties, and Rayleigh scattering.

In the spectral region from the visible through about 1700 nm, absorption by the OH^- ion and Rayleigh scattering dominate. Absorption arises from the overtones of the fundamental 2.7 μm OH^- lines at 1390 and 950 nm. In most fiber intended for telecommunication applications, manufacturing techniques eliminate the absorption at 950 nm, and the absorption at 1390 nm is no more than a few tenths of a dB (Fig. 5.6.1), and, in some cases, is almost completely eliminated.

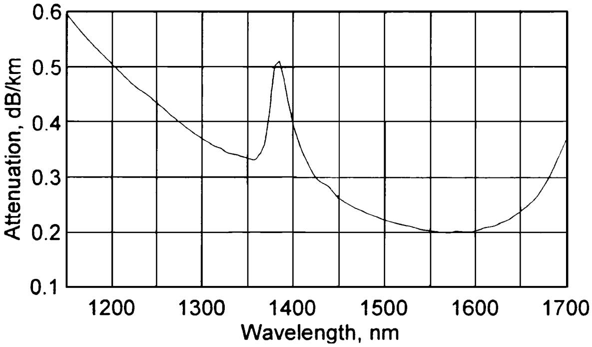

FIGURE 5.6.1 Spectral attenuation of a typical silica optical fiber.
Source: R. B. Kummer, Lucent.

The fundamental mechanism limiting attenuation in glass in the visible and near infrared regions is thus Rayleigh scattering, which varies inversely with the fourth power of wavelength. In this case, the attenuation of power in the fiber is given by

$$P(z) = P(0)e^{-\alpha_R z}$$

where $P(0)$ and $P(z)$ are the power in the fiber at the input and at position z along the direction of propagation, respectively, and α_R is the attenuation coefficient associated with Rayleight scattering. Expressed in dB, the attenuation is given by

$$\text{Attenuation (dB)} = -10 \log \frac{P(z)}{P(0)} \propto \lambda^{-4}$$

Three spectral regions have become important in communications, because fiber properties are favorable and, in some cases, because other components are available for those regions. The first to be exploited was the region around 850 nm, away from the 950 nm OH^- absorption, and where GaAs lasers and LEDs, as well as Si detectors, were readily available. This region continues to be used for short distance systems such as local area and premise networks.

The second is the region around 1300 nm, where Rayleigh scattering is about a factor of 5 lower and, as discussed below, chromatic dispersion is very small. While this region also remains of interest, for high-performance systems it has been superceded by systems operating around 1550 nm, where Rayleigh scattering losses in the fiber are still lower and, more importantly, high-performance optical fiber amplifiers have been developed. These longer wavelength regions are commonly divided for convenience into "bands." While the terminology has not been formally standardized, common usage is approximately as shown in Table 5.6.1.

TABLE 5.6.1 Optical Communication Bands

Name	Wavelength range, nm
O-band	1260–1360
E-band	1360–1460
S-band	1460–1530
C-band	1530–1565
L-band	1565–1625
U-band	1625–1675

In order to facilitate communications using many wavelengths simultaneously, a technique known as wavelength division multiplexing (WDM), the International Telecommunications Union (ITU) has established a standard frequency grid (Recommendation G.694.1) defined by

$$f_n = 193.1 + n\Delta \quad \text{(THz)}$$

Where n is any integer, including zero, and Δ may be 12.5, 25, 50, or 100 GHz. Using the defined value for the speed of light in vacuum ($c = 2.99792458 \times 10^8$ m/s), the corresponding vacuum wavelengths can be computed, as shown in Table 5.6.2.

TABLE 5.6.2 WDM Channels as Defined in ITU Recommendation G.694.1

Central frequencies (THz) for channel spacing of				Central wavelength
12.5 GHz	25 GHz	50 GHz	100 GHz	
⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮
193.1625				1552.02
193.1500	193.150	193.15		1552.12
193.1375				1552.22
193.1250	193.125			1552.32
193.1125				1552.42
193.1000	193.100	193.10	193.1	1552.52
193.0875				1552.62
193.0750	193.075			1552.73
193.0625				1552.83
193.0500	193.050	193.05		1552.93
⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮

TYPES OF OPTICAL FIBER

A simple optical fiber consists of long thin concentric cylinders of transparent material—an inner *core* having a slightly higher index of refraction than that of the surrounding *cladding*. The difference in index between the two regions is usually 1 percent or less; in glass, both values are typically near 1.5. While glass, and some other materials from which optical fibers are made, is inherently strong, it must be protected from surface abrasion that can cause it to fracture easily. And its performance can be degraded by certain types of bending, especially small quasiperiodic bends, known as microbends.

Most optical fibers are therefore protected with one or more additional polymeric coatings, sometimes called *buffers*, or *buffer layers*.

In a simple, ray-optics, view, a structure of this sort guides light because light incident at high angles (relative to normal) on a region of lower index of refraction is completely reflected. This is the principle of total internal reflection, discovered in the nineteenth century. A more complete electromagnetic analysis allows the structure to be characterized as a waveguide, guiding a finite number of spatial modes, not unlike those of typical microwave waveguides (see Fig. 5.6.2).

Step-Index Multimode Optical Fibers

The optical fibers used in imaging bundles, and those used in the earliest experimental optical communications systems, are known as step-index optical fibers, meaning that the transition from the index of refraction of the core to that of the cladding is abrupt. Generally, the indices of refraction in the core and cladding are fairly uniform.

In a fiber that is used in an imaging bundle, or in illumination, the difference in index of refraction between the core and the cladding is one of the most important parameters, in that it governs the angular field of view for which light can be collected and guided. In an imprecise analogy to microscope systems, the *numerical aperture* of a step-index multimode fiber is given by

$$NA = \sqrt{n_1^2 - n_2^2} = \sin\theta_{\max}$$

where n_1 and n_2 are the indices of refraction of the core and cladding, respectively, and $\theta_{\max}$ is the half-cone acceptance angle for rays that intersect the axis of the fiber.

Numerical aperture, along with the size of the core and the wavelength of the light, also determines how many modes can propagate in the fiber.

Step-index multimode fibers rarely find application in communications, because the different modes propagate at significantly different velocities. Pulses of light that propagate in more than one spatial mode are broadened in time through this process, which is known as intermodal distortion, or sometimes intermodal dispersion. A step-index multimode fiber with a core diameter of 50 μm, and an index of refraction difference $(n_1 - n_2)$ of about 1 percent may have an effective bandwidth of only about 20 MHz in 1-km length.

Graded-Index Multimode Optical Fiber

To reduce intermodal distortion, the refractive index of the core can be tailored so that all modes propagate at approximately the same velocity. The variation in refractive index with radius (the "refractive index profile") that minimizes intermodal distortion (maximizes bandwidth) is roughly parabolic with the highest refractive index on the axis. Sometimes the refractive index profile is specified by fitting index data to an equation of the form

$$n(r) = n_1\sqrt{1 - 2\Delta\left(\frac{r}{a}\right)^g} \quad \text{for } r \le a$$

and

$$n(r) = n_1\sqrt{1 - 2\Delta} \equiv n_2 \quad \text{for } r \ge a$$

where $\Delta \equiv \dfrac{n_1^2 - n_2^2}{2n_1^2}$

$n(r)$ = refractive index as a function of radius

n_1 = refractive index on axis

n_2 = refractive index of the cladding

a = core radius

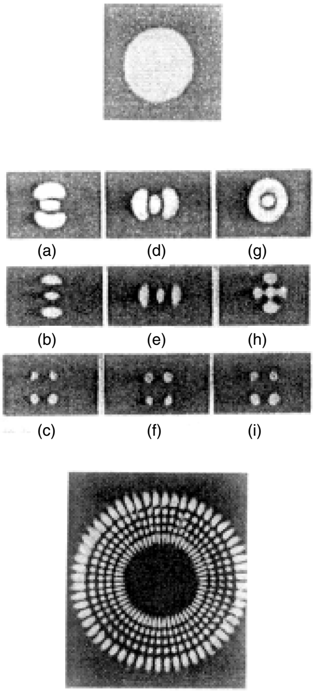

FIGURE 5.6.2 Modes of an optical fiber: Top, the lowest order, HE_{11} or LP_{01} mode; Middle, several low-order modes; Bottom, a high-order mode.
Sources: E. Snitzer and H. Osterberg, *J. Opt. Soc. Am.* 51 499 (1961); W. J. Stewart, Plessey.

The parameter g defines the shape of the index profile and is used in some specifications (e.g., Telecommunications Industry Association specifications TIA-4920000-B, TIA-492AAAB).

Because the refractive indices of glass vary with wavelength, the maximum bandwidth is achieved at a specific wavelength, and may vary dramatically over the wavelength range in which the fiber may be used.

In fibers that are not optimized for maximum bandwidth at the wavelength of operation, the actual bandwidth will depend on the excitation conditions, that is, the manner in which light is coupled into the fiber. Light coupled into a fiber from a light emitting diode (LED) will typically excite most of the modes of the fiber, and often results in the maximum intermodal distortion (minimum bandwidth) for a given length. This specification of bandwidth is sometimes called the *effective modal bandwidth* or the bandwidth with an "overfilled launch." Light coupled into a fiber from a laser will typically excite fewer modes, and may yield a lower intermodal distortion (higher bandwidth), but the bandwidth, in this case, may depend strongly on the specific range of modes excited. Another specification that may be used to describe these effects is *differential mode delay*, which is generally measured by focusing a laser on the core of a multimode fiber and determining the difference in group delay (the propagation time of a short pulse through a specified length of fiber) as a function of the transverse position of the focused spot. Details of various methods of specifying the bandwidth of graded-index multimode fiber can be found in TIA standards TIA-455-220 and TIA-455-204.

The attenuation of multimode optical fiber may also vary among different modes. This effect is sometimes known as differential mode attenuation. As a result, the specification of attenuation is also dependent on the manner in which light is launched into the fiber and, further, the attenuation coefficient may vary with length as modes with higher attenuation disappear. Differential mode attenuation can also cause the bandwidth of the fiber to vary nonlinearly with length. Commonly, an overfilled launch is used for attenuation specifications, but that is the measurement condition for which these effects are usually the greatest. The measurement of attenuation in multimode fiber is specified in TIA-455-46-A and TIA/EIA-455-50-B.

Graded-index multimode fibers are most commonly used in data networks of under 1 km in length, such as access networks and local area networks. Standards for Gigabit Ethernet and 10 Gigabit Ethernet produced by the Institute of Electrical and Electronics Engineers (IEEE), IEEE 802.3z and IEEE 802.3ae, respectively, are based on these fibers.

Single-Mode Optical Fiber

When, for a given difference in index of refraction between the core and cladding, the ratio of the core radius to wavelength is sufficiently small, the fiber will only support one spatial mode, which is commonly designated the HE_{11} (alternatively the LP_{01}) mode. For a step-index fiber, this occurs when

$$\lambda \geq \frac{2\pi a}{2.405}\sqrt{n_1^2 - n_2^2}$$

where a is the core radius.

The value of λ for which this expression is an equality is usually designated λ_c and is known as the cut-off wavelength. The cut-off wavelength is generally determined by observing the apparent change in attenuation that occurs when the wavelength of light passing through the fiber is scanned through the cut-off wavelength (TIA standard TIA/EIA-455-80B). The cut-off wavelength may vary depending on the configuration (such as bends) of the fiber when measured. Manufacturers thus sometimes specify the change in cut-off wavelength that occurs when a fiber is cabled.

The size of the HE_{11} mode is generally specified through a single-dimensional parameter, known as the mode-field diameter (MFD), which varies with wavelength as well as the physical and optical properties of the fiber. The most commonly used definition of MFD is one known as Petermann II. Several measurement methods for MFD are described in TIA standard TIA/EIA-455-191A. Knowing the MFD permits the calculation of loss when fibers with different MFDs are joined; and, for a given optical power level, the larger the MFD, the lower the irradiance in the fiber, which usually leads to a reduction in nonlinear optical effects. Typical single-mode fibers have mode-field diameters in a range of 10 μm.

For purposes of predicting the magnitude of nonlinear optical effects, it is important to know the effective area A_{eff} of an optical fiber. The TIA (TIA/EIA-455-132A) defines the effective area as

$$A_{\text{eff}} = \frac{2\pi\left[\int_0^\infty I(r)r\,dr\right]^2}{\int_0^\infty I(r)^2 r\,dr}$$

which, for a given class of fibers, can usually be estimated by

$$A_{\text{eff}} = k\pi\left(\frac{MFD}{2}\right)^2$$

where k is a constant specific to that fiber class.

Pulses of light propagating in a single-mode fiber increase in duration because of several dispersive effects—the variation of the index of refraction of the glass with wavelength, which leads to variation of the group velocity with wavelength (chromatic dispersion), the variation of group velocity resulting from the parameters of the optical waveguide (waveguide dispersion), and differences in group velocity with polarization (polarization mode dispersion).

Generally, chromatic dispersion and waveguide dispersion are not distinguished in specifications, and sometimes the term *chromatic dispersion* is used to include both effects. Though specifying dispersion versus wavelength might be useful, it is more common to specify two dispersion parameters, the *zero dispersion wavelength* λ_0, and the *zero dispersion slope* S_0, which is the slope of the dispersion near λ_0, and has units of ps/(nm^2 km). For a typical step-index single-mode fiber, sometimes called a *conventional* or *nondispersion-shifted fiber*, the dispersion is dominated by chromatic dispersion, and increases with increasing wavelength, exhibiting zero dispersion at a wavelength between 1310 and 1320 nm. For such fibers, S_0 is typically in the range of 0.1 ps/(nm^2 km), and it is possible to estimate the dispersion at nearby wavelengths $D(\lambda)$ using the expression

$$D(\lambda) = \frac{S_0}{4}\left(\lambda - \frac{\lambda_0^4}{\lambda^3}\right)$$

More complex refractive index profiles can provide waveguide dispersion that differs substantially from that of a step-index profile. This can be exploited to shift the zero dispersion wavelength to another, typically longer, wavelength, or to change the variation of dispersion with wavelength. Fibers in which the dispersion has been shifted to the region around 1550 nm are commonly called *dispersion-shifted* fibers. Fibers that are designed to maintain a low level of dispersion over an extended wavelength range are commonly called *dispersion flattened* fibers. Fibers in which dispersion *decreases* with increasing wavelength are called *dispersion compensating* fibers and can be inserted into a system to reduce the total dispersion.

In WDM systems, nonlinear optical effects can lead to cross talk between channels. Most nonlinear effects are strongest when dispersion is near zero and all wavelengths involved in the process propagate at the same velocity. Maintaining a small but nonzero dispersion over the range of wavelengths used can thus be useful in minimizing cross talk. This has led to the development of various types of "nonzero-dispersion-shifted" fibers, which typically have a zero dispersion wavelength just shorter or just longer than the band in which they will be used. Figure 5.6.3 shows dispersion curves for a variety of fibers.

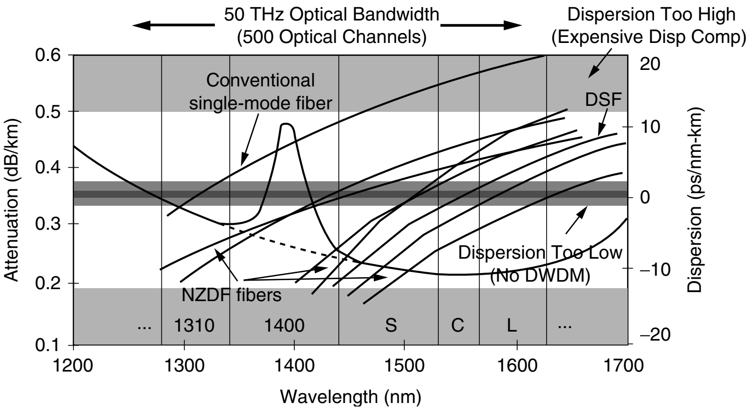

FIGURE 5.6.3 Spectral attenuation of a typical fiber and dispersion characteristics of several types of fiber.
Source: R. B. Kummer, Lucent.

The third source of dispersion in a single-mode fiber arises from the fact that different polarizations within the single spatial mode propagate with slightly different phase and group velocities. These polarization effects arise from stress, either inherent to the fiber or induced mechanically, and imperfections in its cylindrical symmetry. The result is a fiber property known as polarization-mode dispersion (PMD), which, like chromatic dispersion and waveguide dispersion, causes the duration of a pulse to increase as it propagates.

If the polarization properties of the fiber were stable and light did not couple between polarization states, it would be relatively easy to measure and specify PMD. The fiber could be modeled as a combination of a single retarder (a linearly birefringent element) and a single rotator (a circularly birefringent element) and would exhibit an orthogonal pair of stable eigen-polarizations (polarizations for which the output polarization state is the same as the input state). The PMD would be relatively easy to determine and would scale linearly with length.

Instead, the fiber parameters change with the temperature of the fiber and with handling, so PMD can only be specified statistically. Normally, the measurement is of the differential group delay (DGD) between principal polarization states, which are polarization states that, over an appropriate range of wavelengths, represent the fastest and slowest propagation velocities. Theoretically, and well observed in practice, the DGD measured over a range of wavelengths, or over time, follows a Maxwellian distribution, as shown in Fig. 5.6.4. The mean of the distribution is usually called the PMD or mean DGD. Several measurement methods are used, as specified, for example, in TIA standards TIA/EIA-455-113, TIA-455-122-A, TIA/EIA-455-124, and TIA/EIA-455-196.

To further complicate PMD measurements, in long lengths of fiber, light is coupled between polarization states, which tends to decrease the observed DGD. For lengths of fiber long enough for the coupling to be in equilibrium (longer than the “coupling length”) the differential group delay between principal states will increase with the square root of length rather than the length. Similar effects are observed when fibers are concatenated. Methods of addressing these effects, which generally lead to the specification of a *link value* or *link design value* of PMD, are discussed in International Electrotechnical Commission (IEC) Technical Report TR 61282-3.

Single-Mode Fibers with Special Polarization Properties

In certain applications, it may be desirable to use an optical fiber with a very large linear birefringence, that is, a fiber in which orthogonal linear polarizations have significantly different phase velocities. One way to achieve this is to design and manufacture the fiber to have an elliptical core. Another is by incorporating, into the cladding, regions that apply a transverse stress to the core. In either case, the resulting, stress-induced, birefringence can be in the range of 10^{-3}.

Though they may have additional applications, fibers with a large linear birefringence are commonly called *polarization-maintaining fibers*. Linearly polarized light, launched into the fiber with its direction of polarization along one of the axes of birefringence, will tend to remain linearly polarized along that axis, even when the fiber is bent or twisted.

Several methods are used to specify the properties of polarization-maintaining fibers. The beat length, L_B is the propagation distance over which a phase difference between light in the two polarizations of 2π radians

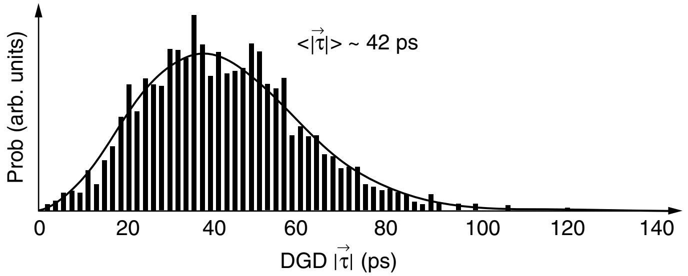

FIGURE 5.6.4 Statistical distribution of differential group delay between principal states showing Maxwellian distribution. PMD is the average DGD.
Source: YAFO Networks.

accumulates. It is given by $L_B = \lambda/\Delta n$, where Δn is the difference in effective (phase) refractive index between the two polarizations and λ is the wavelength. For a typical polarization maintaining fiber, L_B may be in the range of a few millimeters.

Another common specification is *cross talk*, which is generally given for a specific length. This is the fraction of light coupled into the orthogonal polarization when the polarization of the input light is aligned with one of the polarization axes. It is generally given in decibels as

$$\text{Polarization cross talk (dB)} = 10 \log \frac{P_{\min}}{P_{\max}}$$

where, $P_{\min}$ and $P_{\max}$ are the minimum and maximum power levels observed as a polarizer is rotated in the output.

Sometimes, a coupling parameter, commonly known as the *h-parameter* and defined, for a given length L, by

$$\begin{aligned} hL &= \tanh^{-1}\left(\frac{P_{\min}}{P_{\max}}\right) \\ &\approx \left(\frac{P_{\min}}{P_{\max}}\right) \quad \text{for} \left(\frac{P_{\min}}{P_{\max}}\right) \leq 0.1 \end{aligned}$$

is also specified. A typical value for h in a high-quality polarization-maintaining fiber is between 10^{-5} and 10^{-4}.

Fibers Manufactured from Other Glass Systems

Optical fibers made from various fluoride compounds can transmit light in the 2- to 5-μm region. Mixtures of zirconium, barium, lanthium, aluminium, and sodium fluoride have been studied, including a combination of all of these compounds known as ZBLAN. Because the fundamental Rayleigh scattering in that wavelength range would be very small, it was once thought that these fibers could provide levels of attenuation much lower than those of silica fiber. That possibility has not been demonstrated, but fluoride fibers have become useful as hosts for a wide variety of rare-earth dopants, enabling optical amplifiers and lasers to be developed for wavelength ranges where they were not previously available.

Glasses with a high lead content (e.g., SF-57) can have very low stress-optical coefficients, that is, the index of refraction in these glasses is less affected by applied stress than in other glasses. Optical fiber manufactured from these glasses exhibits less birefringence when bent or twisted than ordinary fiber. Because the attenuation in such fiber is relatively high, they are not useful for telecommunications applications, but they may be very useful in certain optical fiber sensor applications.

Plastic Optical Fiber

Optical fiber can also be produced from plastic material, most commonly the acrylic PMMA. Typical plastic optical fibers (POF) are much larger in diameter than silica fibers, often as large as 1 mm, and have a thin cladding. Both step-index and graded-index multimode fibers are available. Generally POF is intended for short-distance applications, perhaps up to 100 m, sometimes within buildings or vehicles.

PMMA fibers have a characteristic spectral attenuation shown in Fig. 5.6.5. Commonly, they are used at a wavelength of about 650 nm, where the attenuation is a local minimum and inexpensive lasers are available.

OPTICAL FIBER CONNECTORS

A wide range of connectors is available for connecting optical fiber; some of the more common designs for single fibers are shown in Fig. 5.6.6. The two key specifications for a connector are the insertion loss and the return loss. For most high-quality connectors, insertion loss is often specified as a maximum value, typically in the range of a few tenths of a dB. The return loss is the fraction of light reflected by the connector. It is usually specified as a positive value in dB (a return loss of 40 dB meaning that the reflected signal is four orders

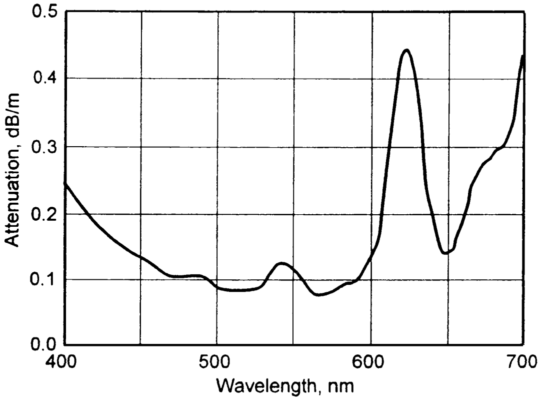

FIGURE 5.6.5 Attenuation of typical PMMA plastic optical fiber.
Source: Mitsubishi Rayon.

of magnitude smaller than the incident signal). Depending on design, connectors are commonly specified to have return loss values between 20 and 60 dB.

Most connectors rely on ceramic ferrules to hold the fibers and align them transversely. In most high-quality connectors, the ferrule and the fiber are polished together and the connectors are designed to bring the two fibers into contact. This is commonly known as a physical contact (PC) design. In some types of connectors the fiber and ferrule is polished at an angle to the axis, which decreases the return loss. This is known as an angled physical contact (APC) design. Connectors are often available factory installed on short lengths of cabled fiber (fiber pigtails) for splicing to a longer length, and on patch cords, with connectors, sometimes with a different connector type on each end.

FIBER COUPLERS

If the cores of two or more fibers can be brought into close enough proximity that the modes overlap to some degree, light will be coupled between or among the fibers. This is most readily achieved by twisting the fibers

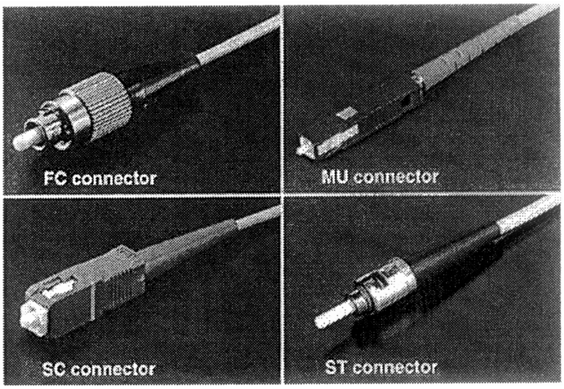

FIGURE 5.6.6 Common types of optical fiber connectors.
Source: Furukawa Electric Co.

together, heating them until they are soft, and pulling until cores reach the desired separation. The degree of coupling will depend on the wavelength, the separation and size of the cores in the interaction region, and the length of the interaction region.

The simplest device based on this principle is a 2 × 2 coupler that can be used to tap a portion of the light propagating in fiber (Fig. 5.6.7). Couplers of this sort are usually designed for a specific wavelength, and are commonly available in tap ratios (ratio of power output from the secondary output port to the total power from both output ports) of 1 (20 dB), 10 (10 dB), and 50 percent (3 dB), among others. Typically the wavelength range over which the tap ratio is maintained within a stated range is specified. Another important parameter is insertion loss, which is typically defined as the total decrease in power in the through-port. For example, a 3-dB coupler may have an *insertion loss* of 3.3 dB, meaning that 50 percent (3 dB) of the light is coupled to the secondary port and 0.3 dB is lost to absorption, scattering, or other effects.

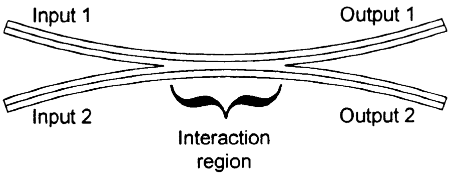

FIGURE 5.6.7 Schematic of a 2 × 2 fiber coupler.

Depending on design and manufacturing processes, the coupling ratio may be strongly wavelength-dependent, and this effect can be used to produce couplers for combining or separating wavelengths. Common applications include separating or combining signals at 1300 and 1550 nm in local networks and coupling pump wavelengths into fiber amplifiers.

FIBER GRATINGS

The refractive index of glass containing germanium can be increased slightly by exposing it to intense ultraviolet light. When this effect is exploited to produce a periodic variation in refractive index along the direction of propagation (a grating), several useful devices can be created. Usually, the manufacturing method involves illuminating the fiber transversely with a laser operating in the 200 to 300 nm spectral range. Periodic variations in the laser intensity can be achieved either by interference of two beams or by using a mask, similar to those used in lithography.

Fiber Bragg Gratings (Short-Period Gratings)

When the spatial periodicity Λ of the variation in refractive index is half the wavelength of light in the fiber, that is, when

$$\lambda_0 = 2n_{\mathrm{co}}\Lambda$$

where λ_0 is the vacuum wavelength, and n_{co} is the effective (phase) refractive index of the LP_{01} mode in the fiber, light will be strongly reflected.

Depending on the details of the grating configuration, very high levels of reflection can be achieved over very narrow spectral ranges, in some cases sufficiently narrow to reflect one wavelength of the ITU WDM grid while transmitting adjacent wavelengths. When combined with other components (e.g., Fig. 5.6.12) this permits the removal of a single channel from a WDM system.

If the periodicity of the grating is chirped, that is, the periodicity varies from one end of the grating to the other, the reflection spectrum is broadened. More importantly, chromatic dispersion is created because light reflected from the far end of the grating is delayed relative to light reflected from the near end. Further, by apodizing the refractive index variation, that is, varying the degree of index modulation along the grating, the delay versus wavelength can be a smooth, quasi-linear, function of wavelength suitable for compensating for dispersion in a fiber. These grating characteristics are illustrated in Fig. 5.6.8.

Because their periodicity is affected by temperature and strain, fiber Bragg gratings can also be used as sensors for those measurands, or for other measurands that can lead to changes in strain or temperature. And

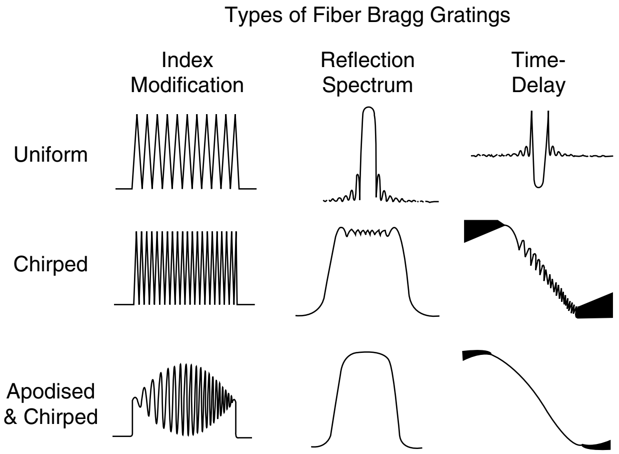

FIGURE 5.6.8 Reflection and dispersion characteristics of several types of fiber Bragg gratings.
Source: Southampton University.

because many fiber Bragg gratings can be incorporated into a fiber or network of fibers, quasi-distributed sensor networks can be developed.

Long-Period Gratings

In addition to coupling light from a forward propagating LP_{01} mode to a reverse propagating LP_{01} mode, gratings can be used to couple light from the LP_{01} mode to either forward or reverse propagating cladding modes. This occurs when the following phase matching condition is met:

$$\lambda_0 = \Lambda(n_{co} \pm n_{cl})$$

where n_{cl} is the effective (phase) refractive index of a cladding mode. The positive sign applies to the coupling between modes propagating in opposite directions, in which the spatial period will be similar to that satisfying the Bragg condition described above. In fact, many fiber Bragg gratings will exhibit transmission minima at wavelengths somewhat shorter than the Bragg condition. The negative sign applies to guided and cladding modes propagating in the same direction. In this case, the spatial period Λ will typically be in the range of several hundred micrometers, hence the term *long-period grating*. Figure 5.6.9 shows the transmission spectrum of a grating with a period of 198 μm, in which the transmission minima correspond to coupling of light into individual cladding modes.

The principal application of long-period gratings is as nonreflective band-rejection filters. They are sometimes used to reject wavelengths in WDM systems, to attenuate amplified spontaneous emission or adjust gain flatness in erbium-doped fiber amplifiers, and to reject Stokes wavelengths in Raman amplifiers.

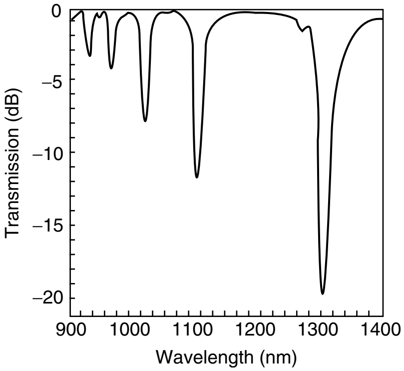

FIGURE 5.6.9 Spectral transmission of a long-period grating.
Source: A. Vengsarkar et al. J. Lightwave Tech., 14, 58–65 (1996).

OPTICAL FIBER ISOLATORS

Isolators are nonreciprocal two-port devices that have a low attenuation in one direction and a high attenuation in the other direction. They are frequently used in optical systems, usually to block light from reflecting back into a laser and damaging it or causing it to become unstable.

Most isolators are based on the Faraday effect, which is a magnetically induced circular birefringence usually observed as a rotation of the plane of polarization of linearly polarized light as it passes through the device. The magnetic field is parallel to the direction of propagation and the plane of polarization is rotated clockwise or counterclockwise depending on the material and whether the light is propagating in the same or opposite direction as the magnetic field.

In a simple isolator, the material, the magnitude of the magnetic field, and the length of propagation in the material are chosen so that the plane of polarization is rotated by exactly 45°, and the rotating element is placed between polarizers that are oriented at 45° to each other. Light entering the device polarized so that it is transmitted through the input polarizer is rotated so that it also passes through the second polarizer. However, light propagating through the device in the opposite direction is rotated so that it is blocked by the input polarizer.

As described, the isolator works well for linearly polarized light, polarized so that it is transmitted by the input polarizer. However, for arbitrary states of polarization, the attenuation in the forward direction is variable and can be high.

A polarization-independent isolator can be built by dividing the input polarization state into orthogonal polarizations, rotating them separately, and recombining them at the output. One implementation of this approach is shown in Fig. 5.6.10. A wedged birefrigent plate causes one linear polarization to be refracted while the other is undeviated. After the plane of polarization of each polarization is rotated 45° by a Faraday rotator, a second wedged birefringent plate, rotated 45° to the first, causes the two polarizations to again propagate in parallel directions, so they can be coupled into fiber. However, for light propagating in the reverse direction, the axial and refracted polarizations are orthogonally polarized, respectively, relative to the forward propagating beam, and are thus refracted at angles that will not be coupled into the fiber.

Optical fiber isolators can usually provide isolation (ratio of the forward to reverse transmittance) in the range of 40 dB, with an insertion loss of less than 1 dB. In multistage, higher performance devices, the isolation can exceed 70 dB.

OPTICAL FIBER CIRCULATORS

Optical fiber circulators, like their microwave counterparts, are multiport devices that use the Faraday effect to direct light from one port to another. In a 3-port circulator, the most common form (Fig. 5.6.11), light entering

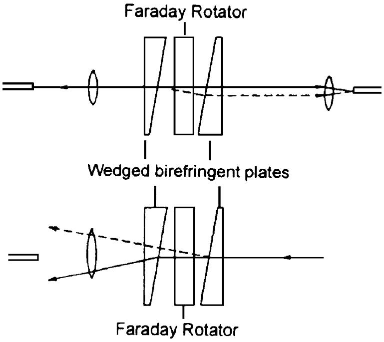

FIGURE 5.6.10 Design of polarization insensitive optical fiber isolator.
Source: M. Shirasaki, U.S. Patent 4,548,478.

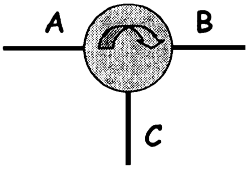

FIGURE 5.6.11 Schematic of a circulator.

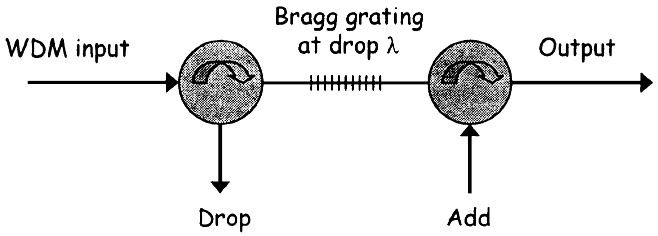

FIGURE 5.6.12 Add-drop multiplexer.

port A is directed to port B; light entering port B is directed to port C, and light entering port C is directed to port A. Most circulators employ Faraday rotation and other technologies similar to those used in isolators.

Circulators are versatile components for manipulating optical signals, as illustrated with the two examples below. Figure 5.6.12 shows how two circulators with a Bragg grating between them can be used to drop and add signals at a particular wavelength. Figure 5.6.13 shows how a single circulator can be used with a chirped fiber Bragg grating to compensate for chromatic dispersion.

WDM MULTIPLEXERS AND WAVELENGTH ROUTERS

In a WDM system, it is necessary to combine and separate (multiplex and demultiplex) different wavelength channels, often large numbers of channels with very small wavelength separations. This can be done with bulk optics and diffraction gratings or thin-film filters, or with combinations of fiber Bragg gratings and wavelength dependent couplers, but most such systems become complex when large numbers of channels are required. An alternative is a planar waveguide device, known (among other names) as an "arrayed waveguide grating (AWG)," and depicted in Fig. 5.6.14.

The AWG is a phased array device, usually produced in silica. Light from each of N input waveguides is divided equally, in an input coupler, among an array of waveguides in which adjacent guides differ in length by a precisely fixed amount. The device is designed so that, for light from a specific input fiber, constructive interference of light from the arrayed waveguides occurs at a specific output port. Thus, one use of the device is as a demultiplexer, as shown in Fig. 5.6.15, which is the superposition of the outputs of an AWG for broadband input light. The AWG is reciprocal, so it can similarly be used as a multiplexer.

The AWG can also be used as a router. If, as illustrated in Fig. 5.6.16, the device is designed so that N wavelengths ($\lambda_1, \ldots \lambda_N$) from input port 3 are directed to output ports N, N–1, . . . , 1, respectively, then the same N wavelengths entering input port 2 will be directed to output ports 1, N, N–1, . . . , 2, respectively. The device is thus a router, permitting one wavelength channel from each input channel to be directed to each output channel.

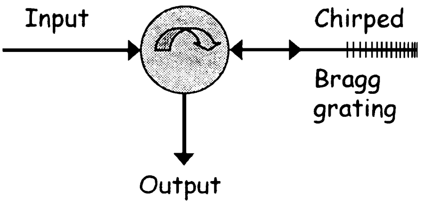

FIGURE 5.6.13 Dispersion compensator.

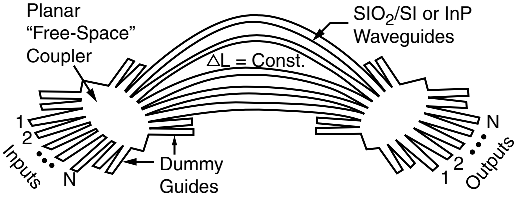

FIGURE 5.6.14 Schematic of an arrayed waveguide grating (AWG).
Source: K. Okamoto, NTT.

SWITCHES

Switches permit networks to be reconfigured, and channels to be rerouted, without conversion from optics to electronics, permitting all-optical networks. For some applications, switching times must be fast, comparable to a data period, but for most applications relatively slow switching is adequate. These slower switches are often called optical cross-connect switches and usually provide the ability to switch the light from any of *N* input fibers to any of *N* output fibers. Several switching technologies have been developed—optomechanical designs, including those based on microelectromechanical structures (MEMs); thermo- and electro-optic effects in planar waveguides; and liquid/bubble filled waveguides. Some approaches are wavelength selective and others are wavelength independent.

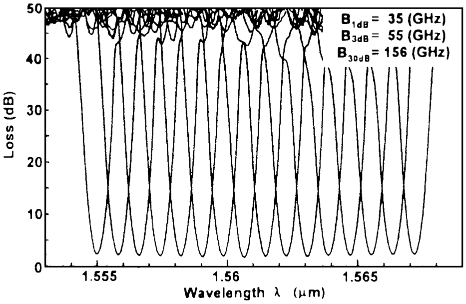

FIGURE 5.6.15 Demultiplexing properties of a 16 channel, 100 GHz spacing AWG.
Source: K. Okamoto. NTT.

One common switch structure is based on 2 × 2 switches in which the two input ports are either connected to the two corresponding output ports (1→1, 2→2) or to the opposite output ports (1→2, 2→1). Arrays of these switches can provide *N* × *N* switching, as shown in Fig. 5.6.17. Note, however, that not all switching combinations are possible. For example, in Fig. 5.6.17, if input port 1 connected to output port 1, then input port 2 cannot be connected to output ports 2, 3, or 4. This is known as *blocking*.

Figure 5.6.18 shows two approaches to the construction of *N* × *N* nonblocking switches based on MEMs technology. In Fig. 5.6.18*a*, a two-dimensional array of N^2 MEMs mirrors, which can be independently positioned either in or out of the beam, provide the switching. In Fig. 5.6.18*b*, two arrays of *N* MEMs mirrors are used. This approach uses fewer mirrors, but the mirrors require greater positioning control.

FIBER AMPLIFIERS

Optical amplifiers permit an optical signal to be amplified, preserving whatever modulation may be present, and allow designers to compensate for attenuation in fiber, losses in other components, and coupling between components. Perhaps most importantly, they can simultaneously amplify many different wavelengths and they are thus the principal enabler of WDM technology.

Three principal types of optical amplifiers are available: semiconductor optical amplifiers (SOAs), which are based on the same compound semiconductor technologies used in semiconductor lasers (SOAs are outside

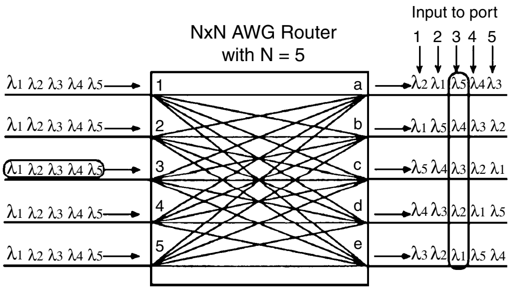

FIGURE 5.6.16 Wavelength routing, as may be accomplished with an AWG.
Source: K. Okamoto, NTT.

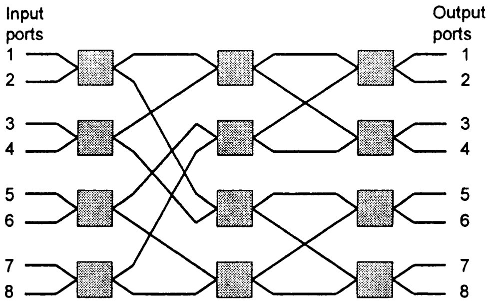

FIGURE 5.6.17 An 8 × 8 cross-connect switch based on twelve 2 × 2 switches.

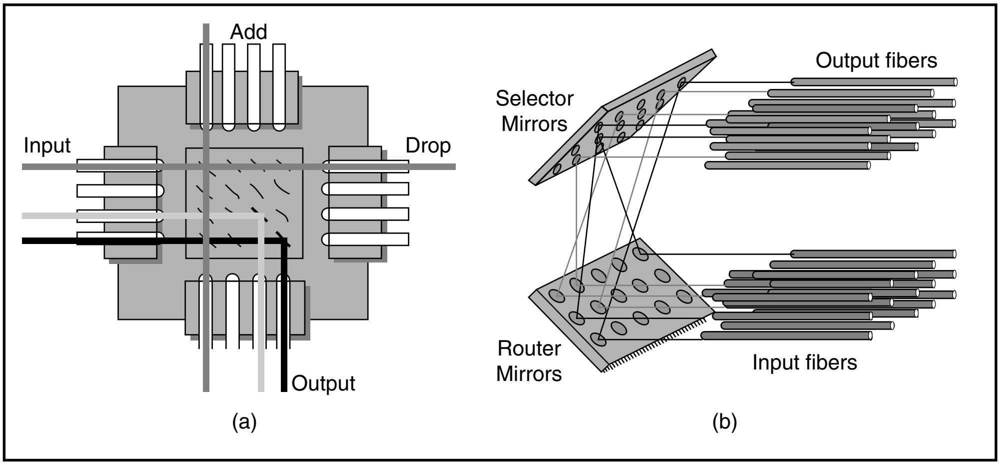

FIGURE 5.6.18 Two configurations nonblocking $N \times N$ cross-connect switches based on MEMs mirrors.
Source: Optical Micromachines.

of the scope of this section); rare-earth-doped fiber amplifiers, in which the gain is provided by any of several rare-earth ions, incorporated into a fiber and pumped by an appropriate laser source; and Raman fiber amplifiers, in which the gain is provided by the Raman effect in ordinary transmission fiber.

Rare-Earth-Doped Fiber Amplifiers

At least eight of the rare-earth lanthanide ions have been shown to provide optical gain when incorporated into silica or other glass hosts—praseodymium (Pr), neodymium (Nd), terbium (Tb), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb)—alone or in combination. In principle, these ions provide the possibility of gain through most of the spectral region from less than 1300 nm to greater than 1600 nm.

Erbium-Doped Fiber Amplifiers. Of the rare-earth-doped fiber amplifiers, the most successful have been those based on erbium-doped silica fiber. The erbium-doped fiber amplifier (EDFA) is important because it provides gain in the 1535- to 1565-nm region, spanning the region of lowest attenuation in a silica fiber, and it has proven effective and reliable. Alternate host glasses, including tellurium-oxide-containing glass can extend the spectral region to wavelengths greater than 1600 nm.

Figure 5.6.19 shows a diagram of the basic elements of an EDFA. At the center is a length of Er-doped fiber, perhaps 10 to 20 m long, which is pumped with the light of one or two pump lasers, usually operating at either

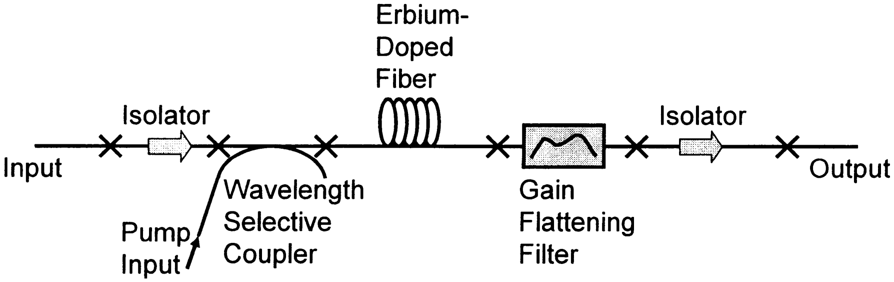

FIGURE 5.6.19 Schematic of an erbium-doped fiber amplifier (EDFA).

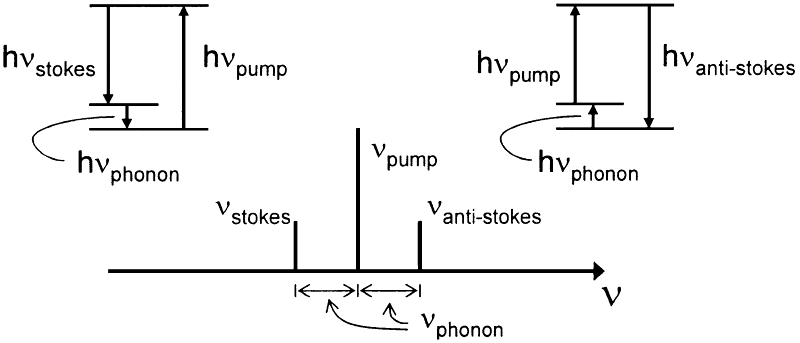

FIGURE 5.6.20 Energy levels and frequencies corresponding to Stokes and anti-Stokes amplification.

980 or 1480 nm, and coupled into the amplifying fiber through WDM couplers. Pumping at 980 nm generally provides lower noise, but may have a lower efficiency. Isolators before and after the amplifier suppress retroreflections.

The small-signal gain typically exhibits a peak at around 1530 nm and a broad shoulder on the longer-wavelength side of the peak. In WDM systems where it is desirable that each channel experience the same gain, filters may be incorporated into the design to flatten the gain spectrum; gain flatness of ±0.5 dB or better is often achieved in this way.

Depending on doping levels, fiber length, and pump power, the amplifier may provide a peak gain of 20 dB to more than 30 dB. When the input power level is such that the upper level of the amplification transition in Er is depleted, the gain saturates. Corresponding output powers may be as high as 100 mW or more.

Noise in EDFAs arises principally from amplified spontaneous emission (ASE), which depends on fiber properties and on pump power and wavelength. Noise figures in the range of 4 to 6 dB are typical.

The ITU, which provides several recommendations on the description of optical fiber amplifiers (Recommendations G.661, G.662, and G.663), categorizes EDFAs into three types: *booster power amplifiers*, which are high saturation power devices intended to be used with a transmitter to increase signal power lever; *preamplifiers*, which are low noise devices intended to be used with an optical receiver to improve sensitivity; and *line amplifiers*, which are used between passive fiber sections to compensate for fiber attenuation and other component losses.

Other Rare-Earth-Doped Fiber Amplifiers. Praseodymium-doped fiber amplifiers, usually pumped around 1017 nm, provide high gain and high saturation power in the 1280- to 1340-nm region, spanning the wavelength of zero-chromatic dispersion. Unfortunately, amplification in the Praseodymium ion works best when the host is fluoride fiber, which is not as well developed as silica fiber.

Thulium, or thulium-ytterbium co-doping, in fluoride fibers has been shown to provide useful gain at wavelengths generally in the S-band, when pumped with a Nd:YAG laser at 1064 nm, and neodymium-doped fibers can provide amplification in the 1320-nm region.

Raman Fiber Amplifiers

In some respects, optical fiber amplifiers based on the Raman effect provide an attractive alternative to rare-earth-doped fiber amplifiers. For a given gain, they require a higher pump power, but Raman fiber amplifiers can provide amplification in any transmission fiber and, when a suitable pump source is available, provide gain at any wavelength where the fiber is transparent. When the pump and signal propagate in opposite directions, the Raman amplifier can provide very low effective noise.

The Raman effect is based on the coupling of light among an intense pump, a low-level signal, and optical phonons, which are mechanical oscillations that have frequencies characteristic of the material and are strongly damped. As shown in Fig. 5.6.20, gain can be achieved at frequencies corresponding to both the difference and sum of the pump and phonon frequencies. These are known as the “Stokes” and “anti-Stokes” frequencies, respectively. In silica, the phonon spectra peaks roughly 12 THz (~90 nm) away from the pump frequency (Fig. 5.6.21).

Raman amplifier products are generally pump modules that consist of an ensemble of high power lasers, often four but experimentally as many as 20 or more, with control electronics to control the power of each laser independently. This permits tailoring the gain spectrum to acceptable flatness. Usually the amplifiers are designed to use Stokes amplification, which is more stable than anti-Stokes amplification. Raman amplification is polarization sensitive, so it is common to incorporate polarization diversity into optical systems associated with the pump.

It is also common to insert the Raman pump module into a system so that the pump propagates in the opposite direction from the signal. Thus, the greatest amplification is achieved where the signal would otherwise have been attenuated to its minimum level. This improves overall noise performance.

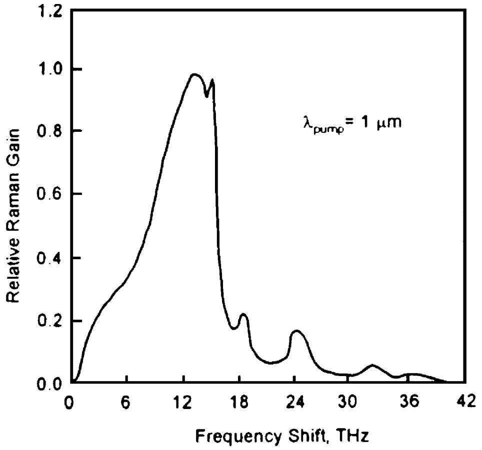

FIGURE 5.6.21 Raman spectrum of a germano-silicate fiber.
Source: R. Stolen, *Proc. IEEE* 68, 1232 (1980).

STANDARDS

Standards cited can be obtained from the following sources:

International Telecommunications Union (ITU)
Place des Nations
1211 Geneva 20
Switzerland
http://www.itu.int

International Electrotechnical Commission (IEC)
3, rue de Varembé
P.O. Box 131
1211 Geneva 20
Switzerland
http://www.iec.ch

Telecommunications Industry Association (TIA)
(Member of Electronic Industries Alliance, EIA)
2500 Wilson Blvd., Suite 300
Arlington, VA 22201 USA
http://www.tiaonline.org

Institute of Electrical and Electronics Engineers (IEEE)
Customer Service
445 Hoes Lane
Piscataway NJ 08855-1331 USA
http://standards.ieee.org

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