CHAPTER 3

THE OPTICAL WAVEGUIDE: THE FIBER

3.1 INTRODUCTION

Fiber has become the transporting medium of choice for voice, video, and data, particularly for high-speed communications. Compared with copper cables (twisted pair and coax), fiber is compact and has many properties that copper solutions do not have. For example, fiber is immune to electromagnetic interference, does not corrode, and has (for all practical purposes) an almost unlimited bandwidth: the useful bandwidth per single fiber strand is one thousand times the total radio bandwidth worldwide (i.e., 25 Tb/s vs. 25 Gb/s). However, fiber requires connectors, and specialized personnel to splice and connect fiber cables. Overall, the installation of fiber is dominated not by the cost of the fiber cable itself (which is a fraction of a U.S. dollar per meter) but by the cost of licenses needed to cross fields, the expenses associated with underground conduits, pipes or aerial cable, specialized equipment installation, and the cost of labor. Here, we examine the manufacturability of fiber and its ability to transmit light.

3.2 ANATOMY OF A FIBER CABLE

A typical single optical fiber consists of a strand of ultrapure silica mixed with specific elements, the *dopants*. Dopants are added to adjust the refractive index of silica and thus its light propagation characteristics.

The optical cable is a single strand of fiber, many miles long. It consists of several layers. The innermost layer is the silica *core*. The core is covered by another layer of silica with a different mix of dopants, known as *cladding*. The cladding is covered with a buffer coating, which absorbs mechanical stresses during handling of the cable. The coating is covered by a strong material such as Kevlar™. Finally, a layer of plastic material covers these layers (Figure 3.1). The final fiber cable used in long-haul communications consists of a bundle of optical fibers. Some cables have up to 432 fibers.

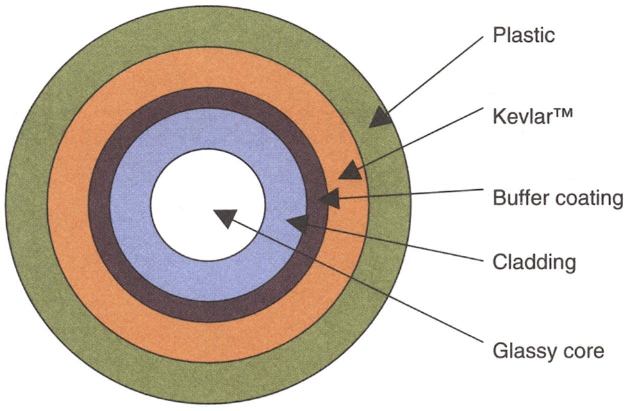

Figure 3.1 Anatomy of a fiber.

3.2.1 How Is Fiber Made?

Fiber is made by vertically drawing a cylindrical preform made of ultrapure SiO_2 in which dopants (e.g., GeO_2) have been added in a controlled manner. The various dopants, which are homogeneously distributed in tubular fashion, determine the refractive index profile of the fiber. The base of the preform is heated at 2000°C (where silica starts melting and becomes viscous) in a high-frequency doughnut-shaped furnace (Figure 3.2).

As the fiber is drawn, its diameter is continuously monitored, and minute adjustments are made (via an automatic control mechanism) to ensure that the fiber is produced with tight diameter tolerance.

3.2.2 How Is the Preform Made?

The cylindrical preform is made by one of several methods, such as vapor phase axial deposition (VAD), outer vapor deposition (OVD), or modified chemical vapor deposition (MCVD), invented in 1970 by scientists at Bell Laboratories.

In the MCVD method, oxides and oxygen enter a rotating, highly pure silica tube in a specified sequence. The tube is maintained at a very high temperature so that chemical interaction with silica and dopant elements (Ge, B, etc.) takes place in a controlled manner. The products of reaction are deposited in the interior walls of the preform evenly. As deposition takes place, the opening of the tube closes in (Figure 3.3). The even and radial deposition of the elements in the preform determines the profile of index of refraction of the fiber, when it is drawn.

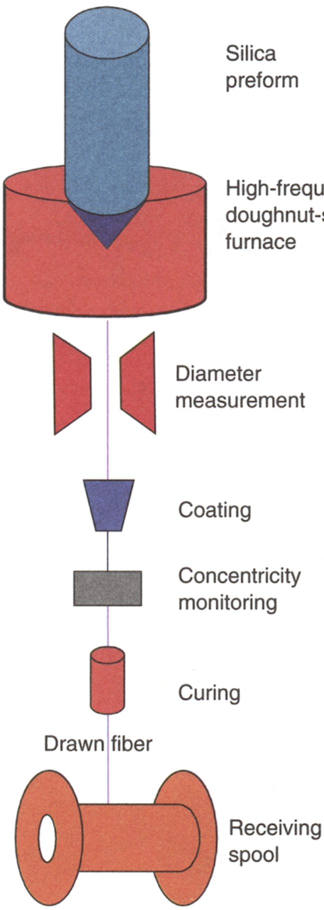

Figure 3.2 Making a fiber.

The highly pure silica tube is manufactured using a typically proprietary method. Lucent Technologies uses a method called *sol gel* (described and illustrated in http://www.bell-labs.com/org/physicalsciences/projects/solgel). Sol gel is made in five phases. In phase 1, a colloidal suspension of silica particles is gelled and cast to form a tube. In phase 2, the gel is removed under water to produce a porous solid tube. In phase 3, the tube is slowly dried without cracking. In phase 4, the tube is placed in a furnace and heated in the presence of various gases to remove water, organic compounds, and other impurities. In the last phase, the porous purified tube is sintered; that is, the purified tube is consolidated to clear glass in chlorine, oxygen, and helium gasses. Then, an MCDV rod is inserted in the core of the sol gel tube and both are collapsed to one solid preform. The fiber is drawn from this preform.

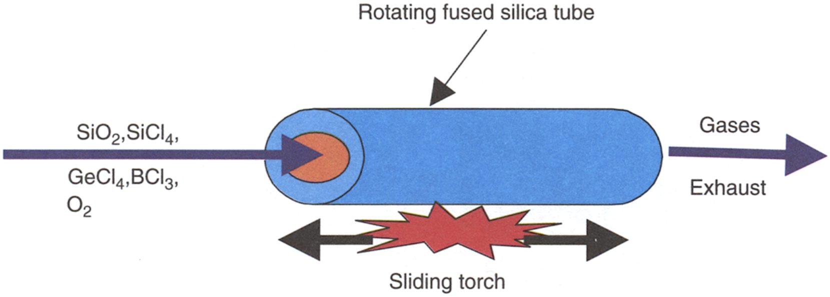

Figure 3.3 Making a preform with the MCDV method.

3.3 INDEX OF REFRACTION PROFILES

The refractive index of the core and the cladding of a fiber are radially controlled during the manufacturing phase to produce an index profile of a shape in one of several forms, such as *step* (Figure 3.4), *Gaussian, triangular,* or more complex. The refractive index profile is formed by controlling the type and amount of dopants in the preform. Dopants increase or decrease the refractive index. For example, zinc sulfide increases the refractive index, whereas magnesium fluoride lowers it. Some typical refractive indices are: GeO_2 (at 2 mol%) 1.461, B_2O_3 (at 8 mol%) 1.458, and P_2O_5

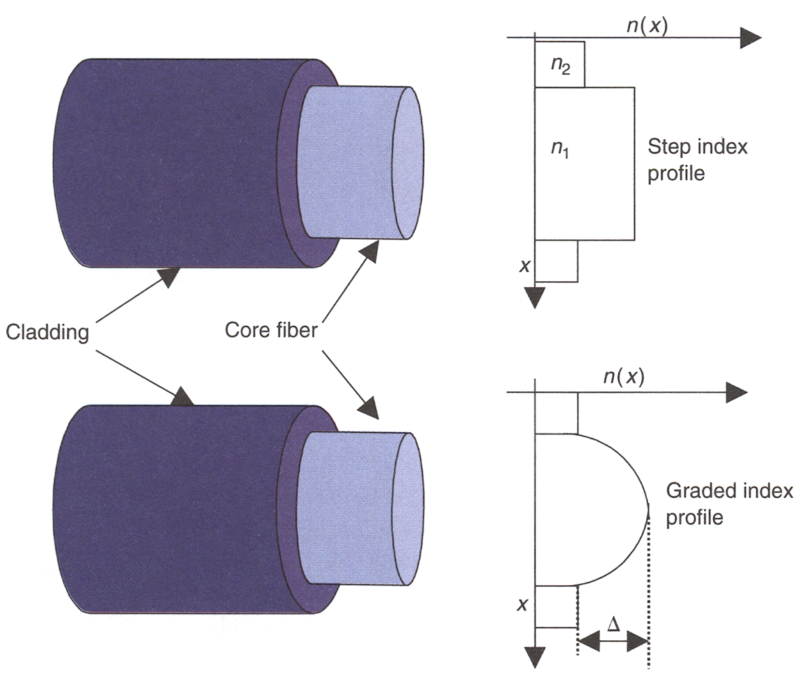

Figure 3.4 Step index and graded index profiles in fiber.

(at 2 mol%) 1.460. Chalsogenide materials have a higher refractive index, such as CdTe at 1.2 μm which has $n = 2.7$.

3.4 FIBER MODES

The propagation characteristics of light in silica fiber depend on the chemical consistency (silica + dopants) and the cross-sectional dimensions of core and cladding. Typically, core and cladding have a diameter of about 125 μm, but the core itself comes in two different dimensions, depending on the application for which the fiber is intended. Fiber with a core diameter of about 50 μm is known as *multimode* fiber, whereas fiber with a core diameter of 8.6 to 9.5 μm is known as *single mode* (per ITU-T G.652) (Figure 3.5). In the following discussion, we examine the reasons for having cores of different dimensions.

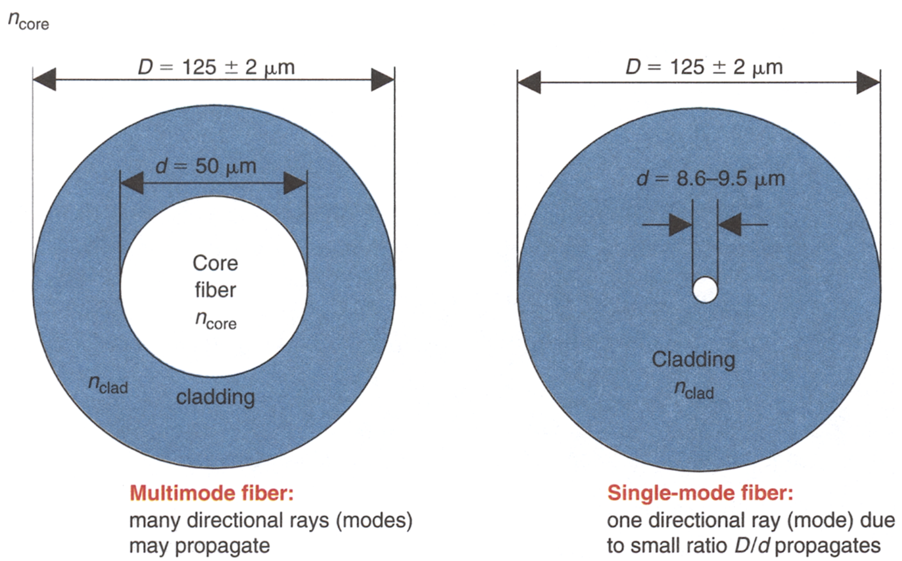

Figure 3.5 Multimode and single-mode fiber cross section.

Optical fiber transmission takes place through guided modes. The modes are determined from the *eigenvalues* of second-order differential equations and their boundary conditions, by an analysis similar to that used for propagation in cylindrical waveguides. Solution of these equations also determines the *cut off frequency*, beyond which the waveguide does not support transmission.

Modes are labeled as TE_{MN} or TM_{MN} (where M and N are integers), depending on the value of the *transverse electric field* ($E_Z = 0$) or the *transverse magnetic* field ($H_Z = 0$) at the surface of the fiber core (the boundary) in the transverse direction. Fibers, based on their dielectric constant and dimensions, support the fundamental mode TE_{11} (also known as HE_{11}) or higher modes. Fibers that support many modes are known as *multimode*, and those that support one (the HE_{11}) are known as *single mode*. A single-mode fiber supports transmission along its longitudinal axis (HE_{11}).

Modes may be thought of as specific path eigendirections. The number of modes, M, of a multimode fiber with a step index profile (n_{core}, n_{clad}) is approximated by

$$\left\{\frac{(4\pi/\lambda)\, d\, [(n_{core}{}^2 - n_{clad}{}^2)]^{1/2}}{2}\right\}^2$$

where λ is the wavelength, and d is the core diameter.

Multimode and single-mode fibers have different manufacturing processes, different refractive index profiles, different dimensions, and therefore different transmission characteristics. Consequently, in optical transmission they find different applications. Some of the salient characteristics of multimode graded-index and single-mode fibers are summarized next.

3.4.1 Multimode Graded Index

The multimode graded index process has the following properties.

- It minimizes delay spread, although the delay is still significant.
- A 1% index difference between core and cladding amounts to a 1–5 ns/km delay spread (compare with step index, which has about 50 ns/km).
- It is easy to splice and to couple light into.
- The bit rate is limited: up to 100 Mb/s for lengths up to 40 km; shorter lengths support higher bit rates.
- Fiber span without amplification is limited: up to 40 km at 100 Mb/s (extended to Gb/s for shorter distances for graded index).

3.4.2 Single Mode

The single-mode process has the following properties.

- It (almost) eliminates delay spread.
- It is more difficult to splice and to exactly align two fibers together.
- It is more difficult to couple all photonic energy from a source into it.
- It is difficult to study propagation with ray theory: Maxwell's equations are required.
- It is suitable for transmitting modulated signals at 40 Gb/s (or higher) and up to 200 km without amplification.

3.5 PROPAGATION OF LIGHT

Typically, the ray technique is used to show propagation of light. This graphical and visual technique traces the paths of optical rays as they travel through matter, and in our case through the fiber, depicting diffraction, refraction, polarization, and birefringence. Figure 3.6 uses this technique to show two cases of light propagation in a step index and in a graded-index fiber. The ray technique is used extensively throughout this book.

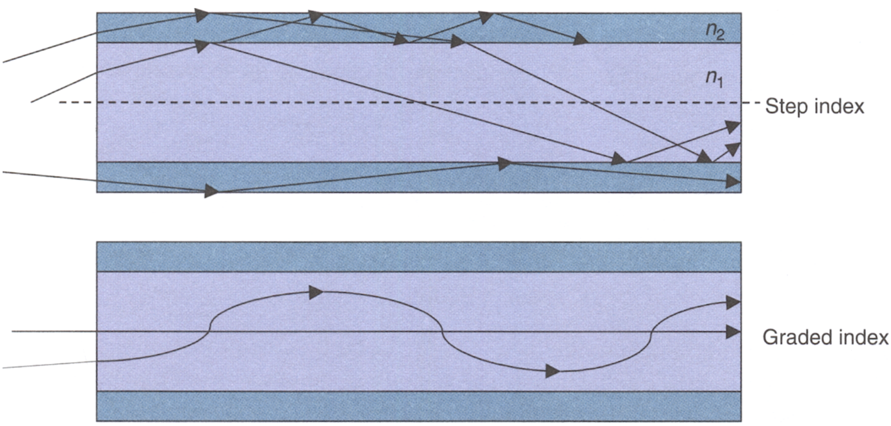

Figure 3.6 Propagation of light rays in step index and graded-index fibers.

3.6 CRITICAL CONE OR ACCEPTANCE CONE

Critical cone, also known as *acceptance cone*, is a cone of an angle within which all rays that are launched into the core are reflected at the core–cladding interface at or beyond the critical angle (Figure 3.7). The half-angle of the critical cone, also known as *numerical aperture*, depends on the refractive index distribution function in the

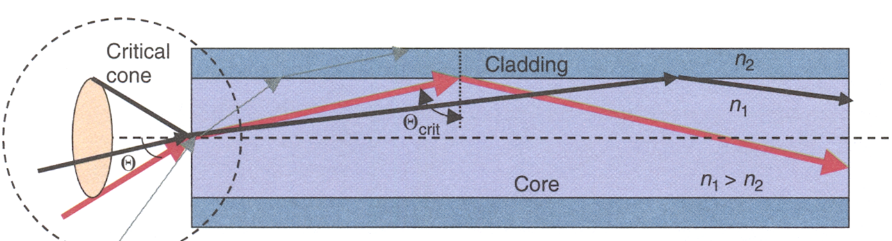

Figure 3.7 Illustrative definition of critical cone.

core and cladding, and is independent of the core diameter. For a step index fiber, the numerical aperture is

$$NA = \sin \Theta_{NA} = (n_1^2 - n_2^2)^{1/2},$$

where n_1 is for the core and n_2 for the cladding.

3.7 EXIT CONE

Similar to the critical or acceptance cone defined at the entry of the fiber, light emerges from the far end of the fiber in a cone. This is known as the *emerging cone.* In single-mode fiber, the exit cone is approximately the same as the acceptance cone. Clearly, for best coupling results, the acceptance cone and the exit cone should be as acute as possible.

3.8 PHASE VELOCITY

A monochromatic wave (single ω or λ) that travels along the fiber axis is described by

$$E(t,x) = A \exp[j(\omega t - \beta x)],$$

where A is the amplitude of the field, $\omega = 2\pi f$, and β is the propagation constant.

Phase velocity V_Φ is defined as the velocity of an observer that maintains constant phase with the traveling field, that is, $\omega t - \beta x =$ constant. Replacing the traveled distance x within time t, $x = V_\Phi t$, then the phase velocity of the monochromatic light in the medium is

$$V_\Phi = \omega/\beta.$$

3.9 GROUP VELOCITY

A modulated optical signal contains frequency components that travel (in the fiber) with slightly different phase velocities. This is explained mathematically as follows. Consider an amplitude-modulated optical signal traveling along the fiber

$$e_{AM}(t) = E[1 + m \cos(\omega_1 t)]\cos(\omega_c t),$$

where E is the electric field, m is the modulation depth, ω_1 is the modulation frequency, ω_c is the frequency of light (or carrier frequency), and $\omega_1 << \omega_c$. Trigonometric expansion of this expression results in three frequency components with arguments:

$$\omega_c, \omega_c - \omega_1, \text{ and } \omega_c + \omega_1.$$

The components travel along the fiber at slightly different phase velocities (β_c, $\beta_c - \Delta\beta$, $\beta_c + \Delta\beta$, respectively) accruing a different phase shift. Eventually, all three components form a spreading envelope that travels along the fiber with phase velocity

$$\beta(\omega) = \beta_c + (\partial\beta/\partial\omega|\omega, = \omega_c)\Delta\omega = \beta_c + \beta'\Delta\omega.$$

Group velocity ($v_g = c/n_g$) is defined as the velocity of an observer who maintains constant phase with the group traveling envelope; that is, $\omega t - (\Delta\beta)x$ = constant. Replacing x by $v_g t$, then, the group velocity is expressed by

$$v_g = \omega/\Delta\beta = \partial\omega/\partial\beta = 1/\beta',$$

where β is the propagation constant and β' is the first partial derivative with respect to ω.

Group velocity is particularly significant in optical data transmission where light is modulated.

3.10 MODAL DISPERSION

An optical signal that is launched into a fiber may be considered to be a bundle of rays. Although a serious effort is made to launch all rays parallel into the fiber, imperfections of optical devices cause rays to be transmitted within a small cone. Because the rays in the fiber are not parallel, the transmission is affected. In the following sections, we examine the effect of this on the quality of the signal and on the band width (bit rate).

3.10.1 Intermodal Delay Difference

Consider an optical signal that is modulated so that optical pulses are coupled into the fiber. Rays A and B in Figure 3.8 are of the same wavelength, and they belong to the same optical signal (pulse); but because they are not parallel, the rays travel different paths along the fiber. These paths are also known as *modes*. Thus, ray A travels in a straight path along the core of the fiber (one mode), whereas ray B travels in an angle bouncing off the cladding (another mode). As a result, the rays travel different total distances and arrive at a distant point of the fiber at different times. Thus, the initial narrow pulse spreads out as a result of modal delays. This is known as *modal dispersion*.

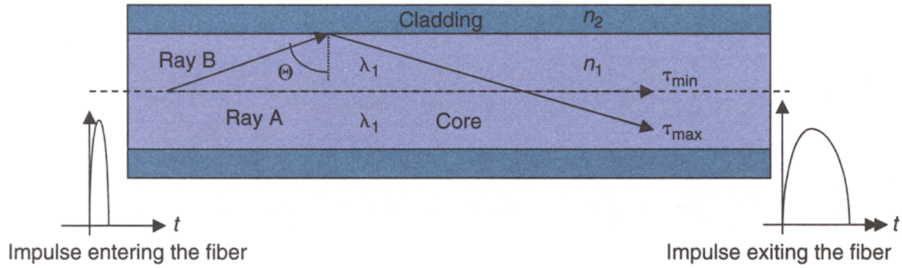

Figure 3.8 Initial narrow pulse spreads out because of modal dispersion.

Clearly, as a pulse spreads out (Figure 3.9), it reaches a point of overlapping with the one that follows it. Obviously, this is highly undesirable in ultrafast digital transmission, where pulses are as narrow as few tens of picoseconds. In digital transmission, the rule of thumb for acceptable dispersion is:

$$\Delta\tau < T/k,$$

and the information (bit rate) limit is expressed by

$$R_b < \frac{1}{k\Delta\tau},$$

where $\Delta\tau = \tau_2 - \tau_1$, R_b is the information (bit) rate, T is the bit period, and k is the dispersion factor (a transmission design parameter, typically selected to $k = 4$). If $k = 5$, then less dispersion is acceptable; if $k = 3$, more is acceptable.

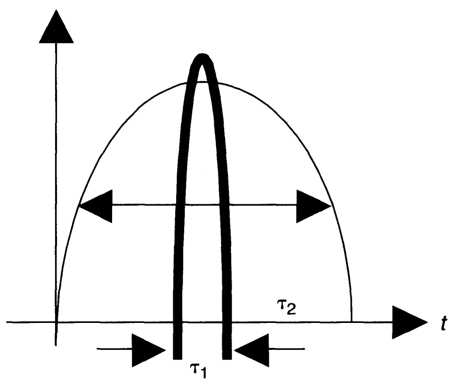

Figure 3.9 Modal dispersion, before and after.

3.10.2 Maximum Bit Rate

The travel time of the two rays (see Figures 3.8 and 3.9) are

$$\tau_{min} = \frac{Ln_1}{v}, \text{ and } \tau_{max} = \frac{Ln_1}{v \cos \Theta}$$

for $\Theta = \Theta_{crit}$ (total reflection) and from Snell's law:

$$\cos \Theta_{crit} = \frac{n_1}{n_2}.$$

The difference in travel time (assuming total reflection) is

$$\Delta\tau = \tau_{max} - \tau_{min} = \frac{Ln_1}{v} \frac{\Delta n}{n_1}.$$

Hence, the maximum bit rate R_b is calculated from

$$R_b < \frac{1}{4\Delta\tau} = \left(\frac{1}{4} \frac{v}{Ln_1} \frac{n_1}{\Delta n}\right).$$

3.10.3 Mode Mixing

Consider the case of two connected multimode fibers. Clearly, the connection of the two fibers presents a perturbation in the optical path. When light rays reach the end of the first fiber, they are launched into the second. However, because there are many modes (i.e., different rays traveling in different angles), the rays enter the second fiber at different angles and thus are refracted differently. Consequently, one mode may change into another mode. This behavior, known as *mode mixing*, occurs only in multimode fibers.

Mode mixing affects the actual transmitted bandwidth (BW_{act}) over the length (L) of a multimode fiber. An empirical *scaling factor*, γ, has been devised to calculate the effective bandwidth:

$$BW_{eff} = \frac{BW_{act}}{L^{\gamma}}, \ \gamma = 0.7\text{–}1.0.$$

3.11 REDUCTION OF MODAL DISPERSION

The difference in travel time is improved if a graded-index fiber is used. For a graded index of refraction profile $n(r)$, dispersion is improved if the condition holds:

$$R_b \leq \frac{2v_g}{n_g L \Delta^2},$$

where n_g is the group refractive index, Δ is the maximum relative index between core and cladding, and v_g is the group velocity in the medium.

Fibers with various graded-index profiles have been made. An example of a profile (Figure 3.10) is

$$n(r) = n_1 \, [1 - 2\Delta(r/a)^{\alpha}]^{1/2}, \text{ for } r < a.$$

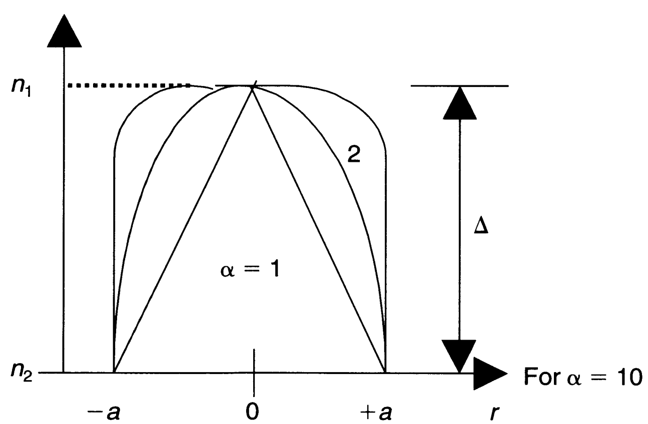

Figure 3.10 Index of refraction profiles to minimize modal dispersion.

3.12 CHROMATIC DISPERSION

The propagation characteristics of each wavelength depend on the refractive index of the medium and on the nonlinearity of the propagation constant. These dependencies affect the travel time of each wavelength through a fiber medium. As a result, an initially narrow pulse is widened because the pulse is not purely monochromatic. This is termed *chromatic dispersion*, or intramodal dispersion (not to be confused with the intermodal dispersion). Chromatic dispersion consists of two contributions: (1) the dependence of the dielectric constant ϵ on frequency ω, known as *material dispersion*, and (2) the nonlinear dependence of the propagation constant on frequency ω, known as *wavelength dispersion.*

Dispersion is measured in picoseconds per nanometer–kilometer (i.e., delay per wavelength variation and fiber length). Material dispersion is the more significant. In the following section we examine both types.

3.12.1 Material Dispersion

The propagation characteristics of each wavelength depend on the refractive index of the medium. The refractive index is also related to the dielectric constant of the medium. Thus, there is a dependence of the dielectric constant on frequency and on wavelength. The propagation characteristics of each wavelength in a fiber are therefore different. Different wavelengths travel at different speeds in the fiber that result in dispersion due to the material.

Thus, when a narrow pulse of light, consisting of a narrow range of wavelengths, is launched in a medium, each individual wavelength arrives at the end of the fiber at a different time, even if all frequencies travel on the same straight path. The result is a dispersed pulse due to *material dispersion* (Figure 3.11).

3.12.2 Wavelength Dispersion

Consider that a narrow optical impulse consists of a narrow range of wavelengths. Thus, wavelengths λ_1 and λ_2 in the same impulse are slightly different. We assume

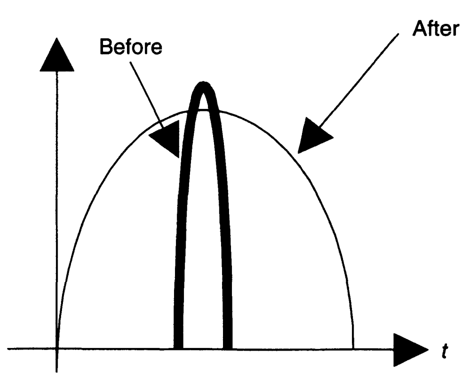

Figure 3.11 Material dispersion of a pulse of light.

that both wavelengths travel (along the core of the fiber) in a straight path, but owing to the nonlinear dependence of the propagation constant on frequency ω (and on wavelength), λ_1 travels faster than λ_2 ($\lambda_1 < \lambda_2$) (Figure 3.12). Thus, although the optical impulse is initially narrow, at a distant point of the fiber, propagation delays cause the constituent wavelengths of the impulse to arrive at different times; this phenomenon is termed *wavelength dispersion.*

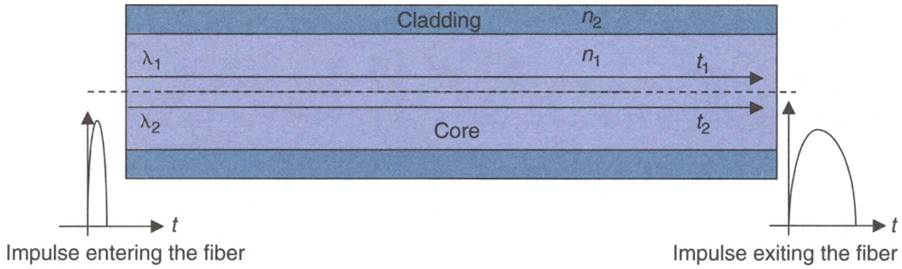

Figure 3.12 Principles of wavelength dispersion.

3.12.3 Chromatic Dispersion: Travel Time Variation

The travel time τ for a group of velocity v_g and a length of fiber L is

$$\tau = \frac{L}{v_g} \quad \text{or} \quad \tau = L\beta' = L\left(\frac{\partial\beta}{\partial\omega}\right),$$

where β is the propagation constant and β' is the first derivative with respect to ω. The variation of τ with respect to ω, $(\partial\tau/\partial\omega)$, is

$$\frac{\partial\tau}{\partial\omega} = \frac{L\,\partial(1/v_g)}{\partial\omega} = \frac{L\,\partial^2(\beta)}{\partial\omega^2} = L\beta'',$$

where β'' is the second derivative with respect to ω.

For a signal with a spectral width $\Delta\omega$, then

$$\Delta\tau = (\beta'')L\,\Delta\omega.$$

That is, the pulse spread (chromatic dispersion) depends on β'' and is proportional to the length of the fiber.

3.12.4 Chromatic Dispersion: Pulse Spread

The *group velocity dispersion* (GVD) coefficient D is defined as the variation of travel time due to the wavelength variation per unit length of fiber L

$$D = \frac{1}{L}\frac{\partial\tau}{\partial\lambda},$$

where ∂ is the partial derivative. The coefficient D is also known as the *chromatic dispersion coefficient.* It follows that

$$D = \frac{1}{L}\frac{\partial\tau}{\partial\omega}\frac{\partial\omega}{\partial\lambda}\cdot$$

However, $\partial\tau/\partial\omega = L\beta''$ and $\partial\omega/\partial\lambda = -2\pi\nu/\lambda^2$ and thus,

$$D = -\frac{2\pi\nu}{\lambda^2}\beta''$$

and

$$\Delta\tau = DL\left[\left(\frac{-1}{2\pi\nu/\lambda^2}\right)\right]\Delta\omega.$$

Finally, the pulse spread, or chromatic dispersion, is expressed by

$$\Delta\tau = |D|L\Delta\lambda,$$

where ∂ has been replaced by Δ and $\Delta\lambda$ is the optical spectral width of the signal (in nm units); chromatic dispersion is also denoted by the Greek letter σ (Figure 3.13).

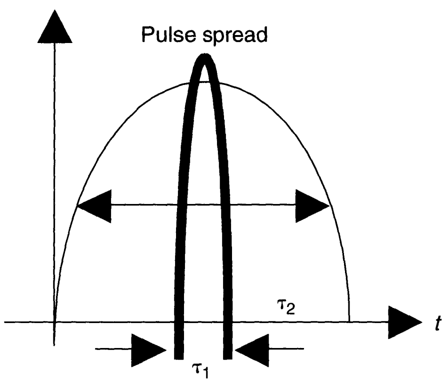

Figure 3.13 Pulse spread due to chromatic dispersion.

3.13 DISPERSION-SHIFTED AND DISPERSION-FLATTENED FIBERS

The dependency of the refractive index of silica fiber is nonlinear. As such, at some wavelength, the derivative $d\{n(\omega)\}/d\lambda$ becomes zero; that is, material dispersion becomes zero. The wavelength where the derivative is zero is called *zero-dispersion wavelength.*

A conventional single-mode fiber with a core diameter of about 8.3 μm and an index of refraction variation of about 0.37% has a zero dispersion at about 1.3 μm. Below this point, wavelength dispersion is negative and above it is positive.

For long-haul transmission, single-mode fibers with specialized index of refraction profiles (by controlling the dopant) have been engineered and manufactured.

A fiber with a zero-dispersion point shifted at 1550 nm (1.55 μm) (i.e., where the minimum absorption for silica fiber is) is called *dispersion-shifted fiber* (DSF). These fibers are compatible with optical amplifiers that perform best at around 1550 nm. Dispersion-shifted fiber with low loss in the *L-band* (1570–1610 nm) provides a wide range of wavelengths making it suitable for DWDM applications. For example, DSF fiber has been installed extensively in Japan.

Another fiber type with near-zero dispersion in the range of 1.3–1.55 μm is called *dispersion-flattened fiber* (DFF). In this category, depending on the dispersion slope, there is *positive DFF* and *negative DFF.* There are also fibers of other types, such as *dispersion-compensated fiber* (DCF), *dispersion flattened compensated fiber* (DFCF), *dispersion-slope-compensated fiber* (DSCF), *dispersion-shift-compensated fiber* (DSCF), and *nonzero dispersion fiber* (NZDF). There are even more specialized fiber types, in addition to erbium-doped fiber amplifiers (EDFA), which are used to amplify optical power.

The TrueWave™ fiber family of Lucent Technologies is a two-member family of nonzero dispersion fibers optimized for wavelength division multiplexing (WDM) applications over long fiber spans (long haul). The TrueWave RS (reduced-slope) member is optimized for minimal dispersion to avoid cross-talk. In addition, the small amount of dispersion it introduces is the same for all wavelengths of a broad spectrum making it suitable for WDM. TrueWave XL is optimized for high-power, dense WDM (DWDM) signals suitable for undersea spans and at rates up to 10 Gb/s per wavelength. Figure 3.14 illustrates the dependence of material and wavelength dispersion in both conventional and dispersion-shifted fibers, as well as a dispersion-flattened fiber.

Some typical dispersion values at 1550 nm are 16.9 for standard SMF and 4.41 for TrueWave RS.

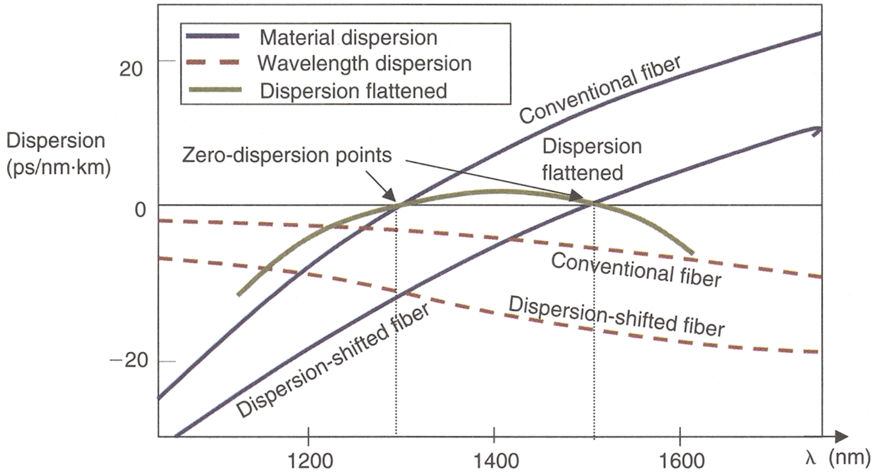

Figure 3.14 Chromatic dispersion graphs for single-mode fiber.

3.14 CHROMATIC DISPERSION LIMITS: ITU-T

The maximum *chromatic dispersion coefficient* (CDC), $D(\lambda)$, is specified by ITU-T G.652, G.653, and G.655. ITU-T G.652 recommends the limits of CDC for single-mode fiber and for wavelengths in the 1260–1360 nm range. In this case, the CDC limits are calculated by

$$D_1(\lambda) = \frac{S_{0\,max}}{4}\left[\lambda - \left(\frac{\lambda^4_{0\,min}}{\lambda^3}\right)\right]$$

and

$$D_2(\lambda) = \frac{S_{0\,max}}{4}\left[\lambda - \left(\frac{\lambda^4_{0\,min}}{\lambda^3}\right)\right],$$

where $S_{0\,max}$ is the maximum zero-dispersion slope set at $S_{0\,max} = -0.093$ ps/(nm^2·km), $\lambda_{0\,min} = 1300$ nm, and $\lambda_{0\,max} = 1324$ nm.

ITU-T G.653 recommends the chromatic dispersion coefficients for dispersion-shifted fiber cables. In this case, the CDC is calculated by

$$D(\lambda) = S_0\,(\lambda - \lambda_0)$$

where S_0 is the zero-dispersion slope [typically ≤ 0.085 ps/(nm^2·km)], λ_0 is the zero-dispersion wavelength (nm), and λ is the wavelength of interest. Assuming a zero-dispersion fiber at $\lambda_0 = 1550$, and λ is within the 1525–1575 nm range, then $D < 3.5$ ps/(nm^2·km).

ITU-T G.655 recommends the chromatic dispersion coefficients for nonzero dispersion-shifted fiber cables. In this case, the CDC should be within the range specified by

$$D_{min} \leq |\,D_{min}(\lambda)\,| \leq D_{max}, \quad \text{for} \quad \lambda_{min} \leq \lambda \leq \lambda_{max},$$

where 0.1 ps/(nm^2·km) $\leq D_{min} \leq D_{max} \leq 6$ ps/(nm^2·km), and 1530 nm $\leq \lambda_{min} \leq \lambda_{max} \leq 1565$ nm.

Fiber cable manufacturers provide chromatic dispersion coefficients by wavelength regions and for each cable type. The total dispersion over a fiber span is calculated assuming a linear dependence on length; that is, the coefficient is multiplied by the fiber length in kilometers.

3.15 SINGLE-MODE CHROMATIC DISPERSION CALCULATIONS

The following is a rough example of dispersion calculations over a fiber link.

Equipment manufacturer model	"APEX, Inc," model F145X	
Bit rate	1.2 Gb/s	
Maximum allowable dispersion	220 ps	
Transmitter wavelength (nominal)	λ_{nom}	1310 (±20) nm
Total fiber span length	L	45 km
Zero dispersion wavelength	λ_0	1310 nm
Dispersion slope at nominal wavelength	S_0	0.1 ps/nm^2-km

Source spectral line width	$\Delta\lambda$	0.5 nm
Chromatic dispersion coefficient at λ_{max} [provided by manufacturer or calculated by equation: $D(\lambda) = (S_0\lambda/4)(1 - \lambda_0^4/\lambda^4)$]	$D(\lambda_{max})$	2.9 ps/nm-km
Chromatic dispersion (calculated)	σ	$\Delta\lambda \times D \times L = 0.5 \times 2.9 \times 45 = 65.25$ ps

The calculated chromatic dispersion, 65.25 ps, is within the system manufacturer's allowable dispersion of 200 ps.

3.16 CHROMATIC DISPERSION COMPENSATION

Clearly, chromatic dispersion has an adverse effect on the ability to transmit at very high bit rates. However, chromatic dispersion is by a good approximation a linear phenomenon, and therefore relatively simple dispersion compensating methods may be applied. A typical dispersion value in standard single-mode fibers is 1 ps/(km-nm).

One of the popular methods is DCF. A dispersion-compensated fiber has a refractive index profile whose effect (on a specific range of wavelengths) is the opposite of that of conventional fibers. Thus, when a DCF fiber is coupled to the transmitting (conventional single-mode) fiber, chromatic dispersion is compensated for the group of wavelengths for which the DCF is designed.

Chromatic dispersion is also compensated by using chirped in-fiber Bragg gratings (see Section 4.4). According to this, adjacent wavelengths in a channel are reflected at different depths of the fiber Bragg grating, thus compensating for the wavelength travel-time variation.

Example (see Ref. 89, end of Part II)

Fifty-five wavelengths, each at 20 Gb/s (at an aggregate bandwidth of 1.1 Tb/s) were transmitted for 150 km using a zero-dispersion fiber designed at 1.3 μm. To use erbium-doped fiber amplifiers, which operate best in the range 1.55 μm, the transmitted wavelengths were selected in this range. The resulting chromatic dispersion would be +15.2 ps/(km-nm) with a dispersion slope of +0.064 ps/(nm^2·km).

However, a DCF was used with a large negative dispersion of −103 ps/(km·nm) and a large negative dispersion slope of −0.18 ps/(nm^2·km). Every 50 km of fiber span, a segment of DCF was inserted for a total of three segments, each with dispersion of −800, −700, and −650 ps/nm at −1545 nm, respectively. Thus, the chromatic dispersion was compensated for, as well as both β' and β'', and D and D', leading to a small total chromatic dispersion of 191 ps/nm for a total fiber length of 150 km. ■

3.17 POLARIZATION MODE DISPERSION

As discussed in Section 2.3.2, birefringence causes an optical (monochromatic) signal to be separated into two orthogonally polarized signals, traveling at different speeds. The same occurs to each pulse of a modulated optical signal; the pulse is separated into two pulses, traveling at different speeds. Thus when the two signals recombine, because of the variation in time of arrival, a pulse spreading occurs. This phenomenon is noticeable in ultra high bit rates (>2.5 Gb/s) in single-mode fiber transmission; it is known as *polarization mode dispersion* (PMD). Moreover, when a stream of very narrow (a few picoseconds) orthogonally polarized pulses with separation of a few tens of picoseconds is transmitted in a fiber, then two sequential pulses interact and generate a stream of pulses at lower amplitude and different polarization. This phenomenon, also encountered in ultrahigh bit rates in single-mode fiber transmission, is known as *polarization mode dispersion* (PMD). The phenomenon is not well understood or theoretically explained, although it has been demonstrated experimentally. It is plausible that manufacturing imperfections may cause the noncircular (but elliptical) core of the fiber to contribute to PMD. In Figure 3.15, two consecutive pulses, one polarized at $+45°$ and the other at $-45°$ produce a third, linearly polarized signal at lower amplitude. It has been shown that as the separation between the two pulses increases, the PMD-generated signal decreases. Optical fibers have a polarization mode dispersion coefficient of less than 0.5 ps/km$^{1/2}$ (see ITU-T G.652, G.653, and G.655). For an STS-192/STM-64 signal (~10 Gb/s), this PMD coefficient value limits the fiber length to 400 km.

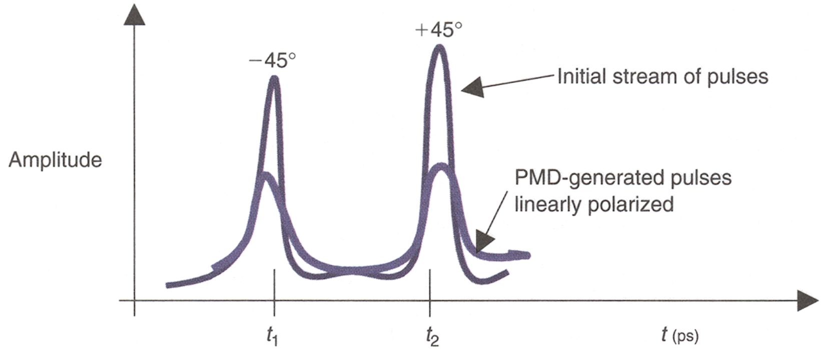

Figure 3.15 In polarization mode dispersion, sequential polarized pulses interact to generate another stream of linearly polarized pulses.

3.18 FIBER ATTENUATION OR LOSS

Fiber attenuation or *loss* is a very important transmission characteristic that imposes a limiting effect on the fiber. Fiber loss, for a given launched optical power into the fiber, $P(0)$, affects the total power arrived at the receiver P_r and thus limits the fiber span L_{max}, without amplification.

Fiber attenuation depends on scattering on fluctuations of the refractive index, on imperfections in the fiber, and on impurities. Metal ions and OH radicals have a particular effect, particularly in the range of 1.4 μm, although fiber cable that is almost free of OH radicals has been successfully manufactured.

Assuming a fiber with an optical power attenuation constant, $\alpha(\lambda)$, the optical power attenuation at a length L is expressed by

$$P(L) = P(0)\ 10^{-\alpha(\lambda)L/10},$$

where $P(0)$ is the launched power into the fiber. If we replace $P(L)$ with P_r, the minimum acceptable power at the receiver, then the (ideal) maximum fiber length is

$$L_{max} = \frac{10}{\alpha(\lambda)} \log_{10}\left[\frac{P(0)}{P_r}\right]$$

Note: We will see that there are additional factors (e.g., dispersion and bit rate) that further limit the (ideal) maximum fiber length.

In general, the optical power attenuation constant $\alpha(\lambda)$ is nonlinear and depends on the wavelength:

$$\alpha(\lambda) = C_1/\lambda^4 + C_2 + A(\lambda),$$

where C_1 is a constant (due to Rayleigh scattering), C_2 is a constant due to fiber imperfections, and $A(\lambda)$ is a function that describes the absorption of wavelengths by impurities in the fiber.

The optical power attenuation constant (dB/km) of a fiber is typically plotted as a function of the wavelength (Figure 3.16). Conventional single-mode fibers have two low attenuation ranges, one about 1.3 μm and another about 1.55 μm. Between these two ranges, at about 1.4 μm, there is a high attenuation range (1350–1450 nm) due to the OH radical with a peak at 1385 nm. This high attenuation range is also known as the "fifth window." Dispersion-shifted fiber has a third low attenuation region in the range above 1550 nm and below 1625 nm.

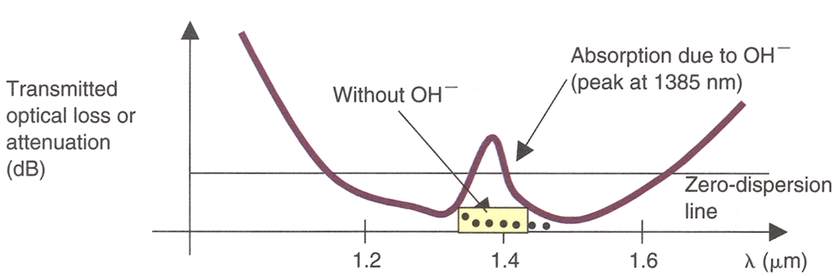

Figure 3.16 Typical single-mode fiber attenuation graph (a zero-dispersion level is included for reference). The Lucent Technologies AllWave™ fiber has eliminated the losses due to OH^- (dotted line).

If the OH radical could be eliminated from the fiber material, the high-attenuation unused region, about 1.4 μm, could be utilized. Clearly, this would make more wavelength channels available. Such a fiber, manufactured by Lucent Technologies as AllWave™ Fibre, has increased the number of wavelengths by over 50% by opening the previously unavailable 1350–1450 nm range (fifth window), thus making all wavelengths, from 1335 nm to 1625 nm, usable. This corresponds to about 500 channels with 100-GHz channel spacing. This type of fiber is suitable for metropolitan area network (MAN) applications.

Fiber attenuation is measured in decibels per kilometer. ITU-T G.652 recommends losses below 0.5 dB/km in the region 1310 nm, and below 0.4 dB/km in the region 1500 nm. Some typical values are 0.4 dB/km at about 1310 nm, and 0.2 dB/km at about 1550 nm. To appreciate the low fiber attenuation, compare it with 1 dB per centimeter thickness of ordinary clear glass or with the 3 dB of ordinary sunglasses.

3.18.1 The Decibel

Optical power attenuation over a fiber span is measured in decibel units (dB). A *decibel* is the logarithmic ratio of received power over transmitted power. Both received and transmitted power are expressed in the same units, and therefore their ratio is dimensionless. Hence, attenuation over a fiber span in dB is expressed by:

$$\alpha(\lambda) = 10 \log (P_1/P_2) \quad \text{(dB)}.$$

Thus, a power ratio of 1000 is 30 dB, a power ratio of 10 is 10 dB, a power ratio of 2 is 3 dB, a power ratio of 0.1 is -10 dB, and so on. Similarly, the signal-to-noise (power) ratio is expressed in dB units.

3.18.2 Examples

In communications, transmitted signals are at extremely low power, in the order of milliwatts. To denote that the reference power point (P_2) is in milliwatts, the decibel unit is expressed as dBm.

Attenuation of several concatenated components, each expressed in decibel units, is additive. Thus, the net power loss of two concatenated components, one with 25.5 dBm and the other with -15.0 dBm is $(25.5 - 15.0) = 10.5$ dBm.

How is –1 dBm derived, and what is its meaning in terms of power launched (in mW)?

1. Calculate the optical power.

   $$-1 \text{ dBm} = -10(1/10)\text{dBm} = 10 \log(1/10) \text{ dBm} = 10 \log (0.1 \text{ mW}/1 \text{ mW}).$$

   That is, the optical power is $P = 0.1$ mW or 10^{-4} W.

2. Convert -1 dBm in optical power density (W/cm^2) if -1 dBm is launched in a fiber core with diameter $D = 10$ μm: The cross-sectional area of fiber is

$$A = (\pi/4)D^2 = (\pi/4)[10 \times 10^{-4}]^2\,\text{cm}^2$$
$$= 0.785 \times 10^{-6}\,\text{cm}^2.$$

The optical power density is:

$$P/A = 10^{-4}\text{W}/[0.785 \times 10^{-6}]\,\text{cm}^2$$
$$= 10^2/0.785\,\text{W/cm}^2 = 127\,\text{W/cm}^2.$$

3. Calculate the optical losses if the laser beam has a diameter of 12 μm and the reflectivity at the fiber surface is 5%. There are two contributions of losses: *A* is due to the difference in cross-sectional area difference between fiber core and beam; B is due to reflectivity.

A, the cross-section of the beam is:

$$A = (\pi/4)D_2{}^2 = (3.14/4)[12 \times 10^{-4}]^2\,\text{cm}^2$$
$$= 0.785\,[1.44 \times 10^{-6}]\,\text{cm}^2 = 1.130 \times 10^{-6}\,\text{cm}^2.$$

Thus, the part of optical power impinging on the core is calculated from:

$$[D/D_2]P = [0.785 \times 10^{-6}/1.130 \times 10^{-6}]\,10^{-4}\,\text{W} = 0.69 \times 10^{-4}\,\text{W}$$

B. From the optical power impinging on the fiber core 95% is coupled in and 5% is lost due to reflectivity. Thus, the power launched in the fiber is:

$$0.95 \times 0.69 \times 10^{-4}\,\text{W} = 0.66 \times 10^{-4}\,\text{W}.$$

The latter is expressed as follows:

$$10 \log (0.66 \times 10^{-4}\text{W}/1\,\text{mW}) = 10 \log(0.066)\,\text{dBm} = 10(-1.18)\,\text{dBm}$$
$$= -10.18\,\text{dBm}.$$

3.19 FIBER SPECTRUM UTILIZATION

Based on optical power loss of fiber, spectrum ranges have been characterized for compatibility purposes with light sources, receivers, and optical components, including the fiber. Thus, the low-loss spectrum for single-mode fiber has been subdivided into smaller regions. The S-band (short-wavelength or second window) is defined in the range 1280–1350 nm. The C-band (conventional or third window) is defined in the range 1528–1565 nm. This is also subdivided into the "blue band" (1528–1545 nm) and the "red band" (1545–1561 nm). The L-band (long-wavelength or fourth window) is defined in the range of 1561–1620 nm. The "new band" (or fifth window) is defined in the range of 1350–1450 nm.

The window in the range of 1450–1528 nm is used in single-mode fiber short-distance networks, such as LAN or MAN, that do not require EDFAs. EDFAs do not perform below 1530 nm, although other amplifier types (Raman scattering, praseodymium-doped fiber amplifiers telluride-erbium-doped fiber amplifiers) may extend the applicability of this range to long-distance networks.

The S- and C-band ranges have found applications in WDM metropolitan networks. The C- and L-band ranges have found applications in ultra-high-speed (10–40 Gb/s) WDM networks. The C-band is popular in the United States and elsewhere. It is compatible with cost-effective optical fiber amplifiers. The L-band is popular in Japan and elsewhere. The L-band takes advantage of the dispersion-compensating fiber that effectively extends the C-band range to 1600 nm, thus doubling the number of wavelengths better suited to DWDM applications. Previously unavailable optical amplifiers and filters in the L-band are now becoming readily available. Moreover, to avoid four-wave mixing phenomena, a proposal to use nonuniformly spaced channels has been submitted and is under study by ITU-T (G.692).

The first window refers to the wavelength range from 820 nm and below 900 nm that is used in multimode fiber applications. Table 3.1 summarizes the frequency utilization.

Table 3.1 Summary of Frequency Utilization for Fiber Application

Window	Label	Range (nm)	Fiber Type	Applications
First	—	820–900	MMF	LAN-type
Second	S	1280–1350	SMF	Single-wavelength
Third	C	1528–1561	SMF	DWDM[1]
Fourth	L	1561–1620	DSF	DWDM
Fifth	—	1350–1450	SMF AllWave™	DWDM
Fifth	—	1450–1528	SMF	DWDM/MAN[2]

[1] DWDM may also include single wavelength applications.

[2] Currently, EDFAs do not perform below the range of 1530 nm.

3.20 SINGLE-MODE FIBER CUTOFF WAVELENGTH

When the electromagnetic wave of light propagates within a guided medium (i.e., fiber), some interesting phenomena occur; the guide puts a limit on the shortest wavelength of the spectrum that can pass through in single mode. The (wavelength) spectrum that passes through the waveguide looks like a high-pass spectrum (for single-mode operation). The theoretical limit of the shortest wavelength depends on the cross-sectional dimensions and on the dielectric that fills the waveguide. The shortest wavelength at which the fiber propagates in single mode is known as the *cut-off*. Below the cutoff wavelength, the fiber behaves like a multimode. Clearly, in optical fibers with complex refractive index profiles, theoretical calculation of the cutoff wavelength is very complicated, not so much because of the geometry of the guide but because of the index profile. However, it can be determined with approximate solutions and by experimentation.

The cutoff wavelength, per ITU-T G.650, is defined as the wavelength that experiences by the waveguide a "fundamental mode power decrease to less than 0.1 dB." Furthermore, ITU-T G.650 elaborates that in this case when many modes are equally excited "the second order (LP_{11}) mode undergoes 19.3 dB more attenuation than the fundamental (LP_{01})" mode.

3.21 FIBER BIREFRINGENCE AND POLARIZATION

An ideal single-mode fiber would support two orthogonally polarized modes, one along the x axis and one along the y axis. However, because ideal fibers cannot be manufactured for lengths of many kilometers, actual fibers exhibit some birefringence.

The *degree of birefringence* is defined by $B = |n_x - n_y|$, where n_x and n_y are indices for the polarized fiber modes. Fiber birefringence leads to a power exchange between the two polarization components in a continuous manner, changing the polarization from linear to elliptical, to circular, and finally back to linear. The length of birefringent fiber through which polarized light undergoes a complete revolution of polarization is defined as *beat length.* The various phases of polarization within the beat length are illustrated in Figure 3.17. The beat length is given by $L_B = \lambda/B$. For $\lambda = 1550$ nm and $B \sim 10^{-7}$, $L_B \sim 15$ m.

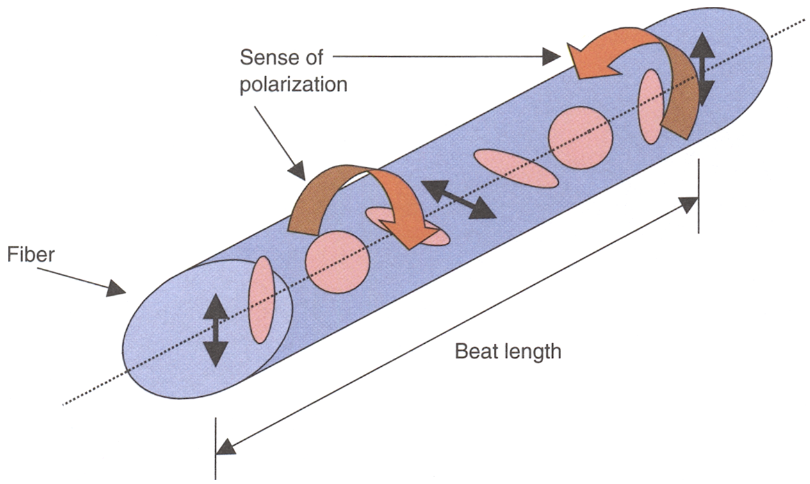

Figure 3.17 Over the beat length, polarized light undergoes a complete revolution of polarization.

In optical communications where a receiver detects directly total intensity, fiber birefringence is not a serious problem. However, it becomes a concern in coherent communications systems where a given direction of polarization is expected, or when polarization-sensitive components are used. To ameliorate fiber birefringence, polarization-preserving fibers have been designed and manufactured. Polarization-preserving fibers exhibit a very strong degree of birefringence ($B \sim 10^{-4}$) such that birefringence induced by core variations, comparatively, becomes negligible.

3.22 NONLINEAR PHENOMENA

When light enters matter, photons and atoms interact and, under certain circumstances, photons may be absorbed by atoms and excite them to higher energy levels. Many atoms, when excited to a higher state, are not stable. New photons may trigger them to come down to their initial, lower energy level by releasing energy, *photons* and/or *phonons* (the acoustic quantum equivalent of light). The photon–atom interaction causes photons to propagate through matter at a velocity that depends on their energy, $E = h\nu$. Thus, different wavelengths travel at different speeds.

In addition to photon–atom interaction, photon–photon and photon–atom–photon interactions also result in some complex phenomena, some of them not well understood yet. These interactions, known as nonlinear phenomena, are best described by quantum theory, and thus we provide only a quantitative description. They are distinguished in *forward scattering* and in *backward scattering* (Raman and Brillouin scattering) as well as in *four-wave (or four-photon) mixing*. The direction (forward and backward) is with respect to the direction of the excitation light. Backward scattering may result from reflected light at the end face (or other discontinuity) of the fiber.

In optical systems, nonlinear phenomena are viewed as both advantageous and as degrading:

- *Advantageous* because they are the basis of lasers, optical amplifiers, and dispersion compensation.
- *Degrading* because they cause signal losses, noise, cross-talk, and pulse broadening.

In general, the input–output relationship of a system is expressed by

$$O = k^1 \cdot I + k^2 \cdot I \cdot I + k^3 \cdot I \cdot I \cdot I + \cdots,$$

where k^n is a higher order system coefficient, O the output, and I the input vector. The first term ($n = 1$) describes the linear behavior of the system, whereas other terms ($n > 1$) describe higher order nonlinear behavior.

The response of any dielectric (such as glass fiber) to optical power is nonlinear; the behavior of dielectric to optical power is like a dipole. It is the dipolar nature of the dielectric that ensures harmonic interaction with electromagnetic waves such as light.

When the optical power is low, it results in small oscillations, and the first term of the series approximates the photon–fiber system behavior (i.e., a linear system). However, when the optical power is large, the oscillations are such that higher order terms (nonlinear behavior) become significant.

Similarly, the polarization of an electromagnetic wave P induced in the electric dipoles of a medium by an electric field E is proportional to *susceptibility*, $\varkappa$:

$$P = \epsilon_o [\varkappa^1 \cdot E + \varkappa^2 \cdot E \cdot E + \varkappa^3 \cdot E \cdot E \cdot E + \cdots],$$

where ϵ_o is the permittivity in vacuum. Here, again, the first term ($n = 1$) describes the linear behavior of the system whereas other terms ($n > 1$) describe higher-order nonlinear behavior.

For an *isotropic* medium the second-order (e.g., silica fiber) is orthogonal. Thus, it vanishes (or it is negligible). However, the third-order results in nonlinear effects that can be significant. Among the nonlinearities, next we examine stimulated Raman scattering, stimulated Brillouin scattering, and four-wave mixing.

3.22.1 Stimulated Raman Scattering

Consider two light sources, one having a short wavelength and the other a longer wavelength, propagating within the same medium. The short-wavelength source excites atoms to a high energy level. Then, the nonlinear properties of the medium cause excited atoms to be triggered by other photons and to "drop" to an intermediate energy level by releasing optical energy of a longer wavelength; this longer wavelength depends on the medium. If the other source is of the same "longer wavelength" with the released wavelength, then optical energy from both "longer wavelength" lights (the original one and the one generated) mix together. Eventually, all atoms at the intermediate level will "drop" to their initially low (or ground) energy level by releasing the remaining energy (Figure 3.18). This is known as *stimulated Raman scattering* (SRS). Raman scattering is dominant when the source is broad band and it may equally occur in both directions in a fiber, forward and backward.

In general, the photon frequency that is emitted when an ion falls from an energy level E_{high} to an energy level E_{low} is determined by the relationship $E = h\nu$:

$$\nu = \frac{E_{high} - E_{low}}{h}.$$

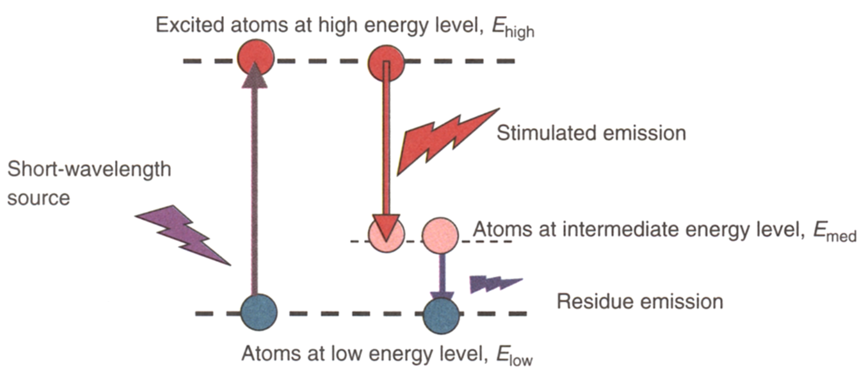

Figure 3.18 A short-wavelength source excites to a high energy level atoms that, when stimulated, release light energy of a longer wavelength.

In optical transmission systems with more than one wavelength in the same fiber, SRS is undesirable because it may result in signal cross-talk, thus restricting the launched power per channel in the fiber. However, for SRS to become a significant cross-talk contributor, the transferred energy must exceed a certain threshold level, which depends on the medium.

SRS is advantageously used to optically amplify a signal. In the latter case, the short-wavelength source acts like a "pump" that transfers energy from it to a modulated weak signal of a longer wavelength.

Example (see Ref. 93, end of Part II)

For a 10-channel system at 1.5 μm with channel separation $\Delta\lambda = 10$ nm (or, $\Delta f = 1.3 \times 10^3$ GHz), the maximum allowable launched power per channel is 3 mW. ■

3.22.2 Stimulated Brillouin Scattering

Stimulated Brillouin scattering (SBS) is the nonlinear phenomenon by which, in contrast to SRS, a signal causes stimulated emission that propagates in the direction opposite to the signal if a threshold power level is reached. In this case, the stimulated light is at a shorter wavelength (downshifted by 11 GHz at 1550 nm). Stimulated emission is in both directions. However, the part that is in the same direction as the original signal is scattered as acoustic phonons, and the part that is in the opposite direction is guided by the fiber. Now, if another optical signal at the downshifted wavelength propagates in the direction opposite to the original signal, it will be mixed with the transferred energy thus increasing signal cross-talk.

It has been experimentally determined that SBS is dominant when the spectral power (brightness) of the source is large, and it abruptly increases when the launched power reaches a threshold value. Factors that determine the threshold value of launched power, include the material of the fiber, the line width of the pump light, the fiber length, the effective cross-sectional area of the fiber core, and the bit rate of the signal.

Threshold values for SBS in fiber systems are in the 5–10 mW range of launched power (for externally modulated narrow line widths) and 20–30 mW for directly modulated lasers (ITU-T G.663).

SBS, like SRS, restricts the launched power per channel. However, SBS may also be advantageously used in optical amplification, where the backward signal may be the pump and the forward signal the one to be amplified.

3.22.3 Four-Wave Mixing

Consider three light wave frequencies, f_1, f_2, and f_3 closely spaced (in terms of wavelength). Then, from the interaction of the three, a fourth lightwave frequency is generated, f_{fwm}, such that $f_{\text{fwm}} = f_1 + f_2 - f_3$. This is known as *four-wave mixing* (FWM, or four-photon mixing). The order of lightwave frequencies is f_1, f_{fwm}, f_3, and f_2 (Figure 3.19).

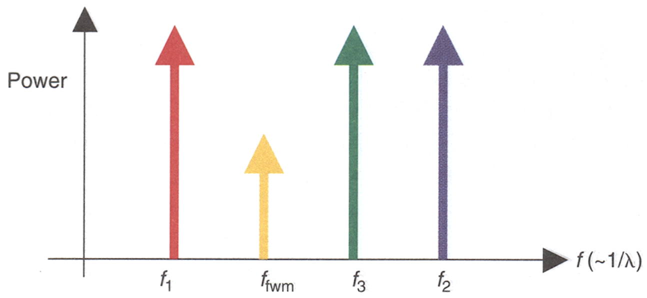

Figure 3.19 In four-wave mixing, three frequencies, f_1, f_2, and f_3 interact to produce a fourth frequency, f_{fwm}, $f_{fwm} = f_1 + f_2 - f_3$.

The output power of the f_{fwm} and the efficiency of four-wave mixing depend on several factors:

- Wavelength mismatch or channel spacing, D_b, or Δf
- Power intensity of the contributing frequencies f_1, f_2, and f_3
- Chromatic dispersion of the fiber
- Refractive index
- Fiber length
- Higher order polarization properties of the material (nonlinear Kerr coefficient)

FWM may also occur with two signals at different wavelengths, if their intensity and wavelengths are in a specific relationship. In such a case, the fiber refractive index is modulated at the beat frequency of the two wavelengths. The phase modulation in this case creates two sidebands (at frequencies given by this difference), the intensity of which is weak compared with the intensity of the mixing products from three signals.

The effect of FWM on optical transmission is signal-to-noise degradation and cross-talk. As the signal input power of f_1, f_2, and f_3 increases, or as the channel spacing decreases, the FWM mixing output term, f_{fwm}, increases. It has been experimentally verified that at 200-GHz channel spacing FWM effects are drastically decreased compared with 100-GHz spacing.

FWM requires strong phase matching (as opposed to SRS, which does not) of coincident energy from all three wavelengths. However, both chromatic dispersion and length of fiber reduce the intensity of the FWM product. In general, FWM limits the channel capacity of a fiber system.

3.22.4 Temporal FWM, Near End, and Far End

Consider a narrow light pulse at a certain wavelength, traveling along a fiber segment. Think of the light pulse as a sliding window with constant speed along the fiber. As the light pulse slides along the fiber, it influences the electric dipoles of the fiber segment for as long as they are in it. If at the same time, there are two more pulses on adjacent wavelength channels, overlapping in time, then in this segment FWM occurs. Because the signal power at the *near end* of the fiber (close to the source) is at its maximum, the FWM product is also at its highest intensity.

Similarly, when the three light pulses arrive at a *far end* segment of a fiber several kilometers long, due to attenuation of the pulses will cause the FWM product at that segment to be at its lowest intensity. Figure 3.20 illustrates qualitatively the contribution of FWM at the near end and at the far end of a fiber. Clearly, FWM occurs in a time-continuous manner, and although at the near end it has a maximum effect, its strength is diminishing as the pulses travel along the fiber. The study of FWM in the time domain is termed *temporal FWM* (tFWM).

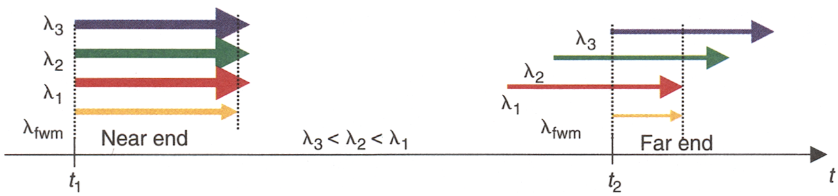

Figure 3.20 FWM of synchronized channels has a maximum effect at the near end, but attenuation and uneven propagation delays serve to diminish its effect at the far end.

3.23 SPECTRAL BROADENING

The refractive index of many materials depends on the amplitude of the electrical field. Thus, as the electrical field changes, so does the refractive index. However, refractive index variations impact the transmission characteristics of the signal itself.

As an almost monochromatic light pulse travels through a fiber, its amplitude variation causes *phase change* and *spectral broadening*. The *phase change* is given by

$$\Delta\Phi = \frac{2\pi(\Delta n)L}{\lambda},$$

where L is the fiber length and

$$\Delta n = n(\lambda,E) - n_1(\lambda).$$

Phase variations are equivalent to frequency modulation, or to "chirping." The *spectral broadening* is given by

$$\delta\omega = \frac{-d(\Delta\Phi)}{dt}.$$

For a *Gaussian*-shaped pulse, spectral broadening is

$$\delta\omega = 0.86\Delta\omega\Delta\Phi_{\mathrm{m}},$$

where $\Delta\omega$ is the spectral width and $\Delta\Phi_{\mathrm{m}}$ is the maximum phase shift in radians.

Spectral broadening appears as if half the pulse has been frequency-downshifted (known as a *red shift*) and the other half frequency-upshifted (known as a *blue shift*). Such shifts are also expected in pulses that consist of a narrow range of wavelengths that are centered around the zero-dispersion wavelength. Below the zero-dispersion point, *wavelength dispersion is negative; above it, positive.* Significant spectral broadening is observed when $\Delta\Phi_m$ is greater than or equal to 2.

3.24 SELF PHASE MODULATION

The dynamic characteristics of a propagating light pulse in a fiber result in modulation of its own phase, due to the Kerr effect of the fiber medium. According to this phenomenon, known as *self phase modulation (SPM),* spectral broadening takes place (Figure 3.21).

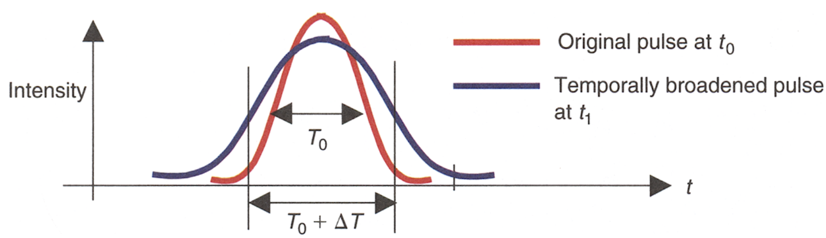

Figure 3.21 The dynamic characteristics of a propagating light pulse in a fiber result in modulation of its own phase that results in spectral broadening.

If the wavelength of the pulse is below the zero-dispersion point (known as *normal dispersion regime*), spectral broadening causes temporal broadening of the pulse as it propagates. If, on the other hand, the wavelength is above the zero-dispersion wavelength of the fiber (the *anomalous dispersion regime*) chromatic dispersion and self-phase modulation compensate for each other, thus reducing temporal broadening. Figure 3.21 illustrates temporal broadening.

3.25 SELF-MODULATION OR MODULATION INSTABILITY

When a single pulse of an almost monochromatic light has a wavelength above the zero-dispersion wavelength of the fiber (known as the anomalous dispersion regime) another phenomenon occurs that degrades the width of the pulse. According to this, two side lobe pulses are symmetrically generated at either side of the original pulse (Figure 3.22). This phenomenon is known as *self-modulation* or *modulation instability.* Modulation instability affects the signal-to-noise ratio and is considered to be a special case of FWM. Modulation instability is reduced by operating at low energy levels and/or at wavelengths below the zero-dispersion wavelength.

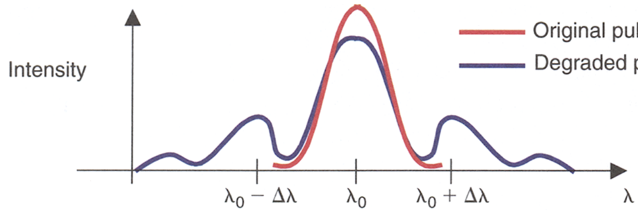

Figure 3.22 Two side lobe pulses are symmetrically generated when the wavelength of a pulse is above the zero-dispersion of the fiber, a phenomenon known as self-modulation or modulation instability.

3.26 IMPACT OF FWM ON DWDM TRANSMISSION SYSTEMS

It is clear that as the density of wavelengths (channels) in DWDM systems increases, cross-talk becomes an important issue in the following cases.

- If the optical power of each channel is increased, FWM becomes more intense.
- If the launched optical power of each channel is lowered, then the actual fiber length is decreased to assure that the arriving signal can be detected reliably. This may necessitate optical amplification (optical amplification increases the cost) to extend the fiber path.
- If the channel (wavelength) density increases, or if the channel spacing decreases, FWM becomes more intense.
- If the channels are spaced further apart, then fewer wavelength channels can be used in the fiber.

3.27 COUNTERMEASURES TO REDUCE FWM

FWM in fiber transmission systems is a phenomenon that cannot be eliminated. However, several countermeasures and design approaches may help to suppress the FWM product.

- Channels can be spaced unevenly, to avoid FWM.
- The channel spacing can be increased to reduce FWM.
- Launched power into the fiber can be reduced to reduce the FWM effect.
- Segments of fibers with opposing nonzero dispersion characteristics after long spans of standard single-mode fiber cable to maintain a near-zero net chromatic dispersion can be used.

3.28 SOLITONS

It has been implied that the contribution of the self-modulation effect (red and blue shift) depends on the pulse shape. Under specific conditions (very short pulses with a specific power spectrum), the spectral broadening due to self-modulation can be compensated for by the dispersion effect of the fiber. In this case, the pulse preserves its input shape and is stable over the entire length of the fiber. Pulses that preserve their shape are known as *solitons*, and the condition for generation and sustained propagation is known as the *soliton regime.*

A theoretical analysis of soliton generation and propagation entails solving a homogeneous Schrödinger-type equation; it is thus beyond our purpose here. However, it should be pointed out that the *soliton regime* involves parameters such as "input optical power" (derived from a *hyperbolic secant* function), "cross section of the fiber core," the "dielectric constant" of the vacuum ($\epsilon_0 = 8.854 \times 10^{-12}$ F/m), and the fiber type.

For a typical single-mode fiber, any real pulse within an area of $A = 1.6\ W^{1/2}$ ps ($\pm 50\%$) can reach the soliton regime; that is, it can generate one soliton. Typical solitons are about 50 ps wide (Figure 3.23). Because of the required pulse narrowness, return-to-zero (RZ) modulation is suitable in solitons (see Chapter 12 for modulation and coding techniques).

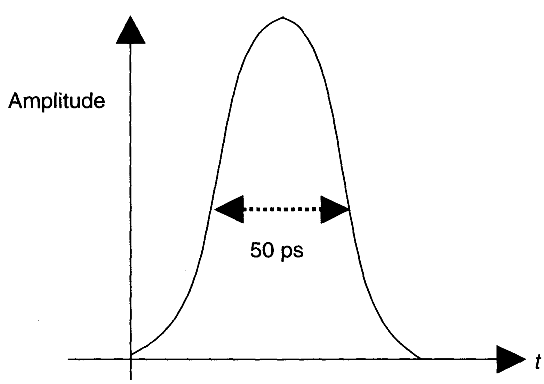

Figure 3.23 Self-modulation of very narrow pulses can be compensated for by the dispersion effect of the fiber, thus preserving the pulse shape; such pulses are known as solitons.

3.28.1 A Qualitative Interpretation of Solitons

As soon as a very narrow pulse is launched into the fiber, its initial pulse shape oscillates temporarily as two competing effects act on it—spectral broadening and compensation by dispersion effects. At some later time, and after a certain fiber length has been achieved, this oscillation finally reaches an equilibrium compensating state and the soliton takes a shape very close to its initial form. However, additional effects may affect the shape of the soliton. Third-order dispersion effects may cause the soliton to change its velocity and thus its shape, and fiber losses will cause the soliton to broaden its width; for example, 15-km travel in single-mode fiber will double the width of the soliton. Therefore, a low-loss single mode with low third-order dispersion characteristics fiber will enable solitons to be transmitted at very long distances and very high bit rates (due to narrowness of the pulses) without amplification.

When solitons are used in WDM systems, an undesirable event may occur—collision among solitons that belong to different channels. Collision takes place over a distance in which solitons overlap. The length of fiber over which solitons of different channels overlap is known as the *collision length*, L_{coll}. The collision length depends on fiber parameters, channel spacing, and the actual bit rate of the colliding channels. Depending on parameter value, the collision length may be 10 km or even 100 km. It has been shown that an exchange of energy takes place during soliton collision. As a result, the soliton frequency and the phase shift cause some residual effects.

At the receiver, because of the *collision-induced temporal shift* and because 1 s and 0 s in the bit stream are random, *timing jitter* is induced (a string of ones would cause the same shift from bit to bit, and thus no jitter). When the collision length becomes comparable to the amplifier spacing, the residual shift (jitter) may become as high as ~0.1 GHz, which is an unacceptable value because jitter is cumulative from amplifier to amplifier.

Clearly, the soliton technique in optical transmission systems is difficult to use because of optical nonlinearities and the high transmitted optical power. However, solitons and dispersion-managed fibers, when used properly, promise an optical transmission technology that exhibits reduced nonlinear effects, high spectral efficiency, RZ modulation, ultrahigh bit rates, and fiber spans at very long lengths (hundreds of kilometers) without regeneration or amplification. The latter prospect makes soliton technology particularly attractive to long-haul and transoceanic optical transmission. Short-haul applications of soliton technology are, for the time being, prohibitively expensive.

3.29 FIBER CONNECTORS

Copper wire may be installed in segments, each segment being connected with another by simply bringing the two ends in physical contact (e.g., by twisting the two ends). Consequently, no special treatment of the two copper ends is required.

Unlike copper wire, fiber requires specialized treatment. Two fiber ends placed one next to the other constitute a material discontinuity. Because photons travel from one fiber to the other, they have to overcome this discontinuity. Consequently, certain special precautions must be taken to minimize power loss as photons travel through it.

- The two fiber ends to be connected should be treated so that the end faces are flat, perpendicular to the fiber longitudinal axis, and highly polished (or forming a spherical lens).
- The two end faces should be treated with antireflective coatings.
- The two fiber cores should be in perfect alignment.
- The two end faces should be brought into close proximity.

The first two precautions are related to the treatment of fiber ends and are accomplished with specialized abrasive materials and coatings. The third is related to how well the fiber has been manufactured (i.e., whether the core is exactly at the center of the circular fiber) and how well interconnecting devices align the cores. The concentricity error of single-mode fiber (based on ITU-T G.652) should be less than 1 μm. The cores are accurately aligned with biconical self-aligned connectors or aligned grooves. Finally, the last item is related to the flatness and perpendicularity of the two end surfaces and to the accuracy of the connectors.

In any case, connector optical power loss must be taken into serious account when one is estimating the overall power loss of an optical link. Because of the stringent power loss budget, fibers are installed preferably in segments many kilometers long, to minimize the number of interconnecting devices.

3.30 CONCLUSION

The quest for a fiber cable that introduces the least optical loss across a wide spectrum of wavelengths, the least dispersion, and almost no nonlinear effects still challenges fiber-optic designers and manufacturers.

However, although the transmission characteristics of fiber cable have been greatly improved, older fibers are still being used. In addition, there is a large variation in fiber specifications among both fiber cables and manufacturers. Clearly, this adds another level of complexity to the design challenges of optical systems, which must be compatible with fibers and vendor equipment of all types. Cost-effectiveness is another important consideration.

Fiber cable as a transmission medium has many highly advantageous qualities. Thus, many telecommunications companies, new and old, install many thousands of kilometers of fiber each year in the ground, along bridges and highways, through high-rise buildings, through natural-gas pipes, along rivers, by train rails, and under the oceans, interconnecting continents, countries, cities, and homes. Thus, one can deduce conclusively that the future of fiber is truly very bright.

EXERCISES

1. Consider a fiber, 1 km long, with a refractive index $n = 1.5$. Consider also a source with a data rate at 10 Gb/s. Calculate the number of bits at any time in the fiber, or the fiber bit capacity. (Approximate the group velocity by $v = c/n$.)
2. Why is the critical cone important in optical communications?
3. In a step index fiber, the core has $n_1 = 1.48$ and the cladding $n_2 = 1.46$. Calculate the numerical aperture (NA) or the critical cone for the fiber.
4. Comment on the cone angle of single-mode versus multiple-mode fiber. Which must be very small?
5. A pulse starts with a width of 30 ps and by the time it has traveled over 10 km of fiber, it is 60 ps. Calculate the maximum bit rate for $k = 3$ c.
6. The OH radical absorbs light energy about 1385 nm. In your judgment, why does OH absorb selectively this wavelength?
7. An optical link consists of three fiber segments, the first 10 km long, the second 30 km, and the third 20 km. The fiber attenuation is 0.1 dB/km. The segments are connected with connectors at 0.1 dB loss each. Calculate the total loss due to fiber and connectors over the link.
8. Is it true that, as the channel spacing increases, so does the FWM contribution?