3

Optical Fiber Performance

3.1 Introduction

Popular thinking holds that optical fibers do not have transmission degradations. In reality there are three basic phenomena that govern their performance and must be taken into account when designing optical fiber systems:

- diminished levels of light at the optical detector caused by *attenuation* or loss of signal energy
- time of arrival differences between the different wavelength components of the signal, referred to as *delay distortion* or *dispersion*
- inability of conventional Silica fibers to maintain *polarization*

The first two, attenuation and dispersion, have been a concern since the beginning of optical fiber use. Polarization performance has become a concern as digital signaling speeds on fibers have progressed beyond 2.5 Gb/s. In designing optical fiber systems, end-to-end performance is generally governed by one or the other of the first two degradations, but generally not both at the same time. Polarization degradations become an added source of distortion for high-speed systems.

In this chapter, silica fiber attenuation is discussed first in Section 3.2. The two main types of silica fiber, multimode and single-mode, do not differ greatly in attenuation. Section 3.3 discusses the wavelength dependent dispersion of silica fibers. This results in a time spread at the receiver, $\Delta\tau$, of components within the signal. Multimode and single-mode fibers differ markedly in dispersion performance. This difference determines their two distinct areas of application: local networking, and long haul. Section 3.4 discusses the polarization performance of silica fibers. Finally, Section 3.5 presents information on the performance of non-silica fibers.

The discussion on attenuation and dispersion that follows assumes the fiber transmitting the signal is part of a linear system. For a system, or system component, to be linear the following has to be true: when two independent signals are input simultaneously the output must be the same as the sum of the two outputs that would result if they were input alone. In a linear system the effect on a signal of one component in the transmission path is independent of other components, and also of the presence of any other signal. A fiber will be non-linear under certain conditions, the most obvious being when too much power is input. Later discussions on solitons and optical amplifiers will show the positive advantages of some optical fiber non-linearities.

The time function of a signal transmitted by a linear system can be described in the time domain as $s_o(t)$. The signal has a related (Fourier Transform) spectral function $S_o(\omega)$. Both of these can be distorted in amplitude and phase by a linear system. The system will have a complex transfer function, $H(\omega)$, where:

$$H(\omega) = \frac{S_o(\omega)}{S_i(\omega)} = |H(\omega)|e^{-j\beta(\omega)} = Ke^{-\alpha(\omega)-j\beta(\omega)}, \text{ where} \qquad 3.1$$

$S_i(\omega)$ = input signal,

$\alpha(\omega)$ = frequency dependent attenuation

$\beta(\omega)$ = frequency dependent phase

This linear system assumption is an important first step in analyzing fiber systems. Later chapters in this book will reveal more complex, non-linear behavior in optical fibers. Amplitude distortion is absent when $\alpha(\omega)$ is flat with frequency. Phase distortion is absent when $\beta(\omega)$ is a straight-line function of frequency (wavelength). Because transmission media always have some frequency (wavelength) performance dependencies, the amplitude function will never be flat and the phase function will never be a straight line. The slope of the phase function depends on the velocity of energy propagation. From Chapter 2, in a fiber waveguide this velocity is called the group velocity. In the absence of distortion, the group velocity will be constant with wavelength.

In radio systems, amplitude and phase distortions within the transmitted spectral bandwidth are important in determining total system performance. This is because of the coherent nature of the total signal, which is a carrier plus modulated sidebands. The amplitude and phase relationship of the sidebands to the carrier must be preserved. Current optical fiber systems use only intensity modulation. An intensity-modulated signal carries the baseband signal by modulating the power of the optical source. The transmitted optical spectrum will have energy in a wide range of frequencies (wavelengths), determined by the spectral width of the source. Amplitude and phase distortions within this band do not affect the modulated baseband signal because the spectral wavelengths generated by the carrier are not coherently related to a central frequency. Attenuation of the total power of the optical signal is important, however. At the receiver the total incoming power must be well above any interference and noise. Also, the phase characteristic $\beta(\omega)$ of the fiber will affect the propagation speed of the carrier's wavelengths. A difference in arrival times of the carrier's wavelengths leads to dispersion distortion of the baseband signal.

Recently developed very high-speed systems using near-single frequency lasers require a different view of the modulated spectrum. An intensity modulated single-frequency source will have a spectral width similar to that of a double-sideband AM signal. With a very narrow carrier width, the transmitted optical spectrum will now be determined by the baseband spectral width. In-band amplitude and phase distortions will still not have to be considered because intensity modulation is still used. This advance is analyzed in Chapter 8. At some future date, when optical sources are as coherent as radio oscillators are now and heterodyne reception can be used, the in-band attenuation and phase will become important in determining system performance. In the electrical signal processing portions of a intensity modulated optical system, baseband attenuation and phase distortions still have to be considered.

3.2 Attenuation

Attenuation is found in almost all optical system components. The fiber is the largest contributor, particularly when maximum transmission distance is a primary goal. Other attenuation contributors between optical transmitter output and optical detector input include: optical source and detector fiber coupling losses; optical networking device losses; connector and splice losses; and a loss margin for unknown loss contributors. A system that just meets a predetermined loss design objective that includes all of these contributors is said to be *power* or *loss limited* (Chapter 7). Losses are almost always expressed in decibels since the use of a logarithmic scale simplifies communication link calculations.

When viewed over their useable range of wavelengths, 600–1600 nm, silica fibers have significant attenuation variation with wavelength ($\alpha(\omega)$). The effect of this shape on an intensity modulated signal using a portion of that spectrum is insignificant. As an example, consider the bandwidth required to transmit the signal from a 1550 nm diode laser, intensity modulated by a 2.5 Gb/s pulse stream. The laser is essentially a non-coherent source (Chapter 4) and its resulting average *linewidth* becomes the transmitted linewidth. The instantaneous center wavelength varies greatly throughout this range. Sidebands in the conventional radio sense do not exist, the optical carrier is not sufficiently stable and sidebands are smeared. A signal like this is incoherent in both space and time. Current commercial communication system receivers are looking only for variations in total intensity to demodulate the signal, not the inter-relationship of frequency components (sidebands) within the signal spectrum. These optical power variations will be occurring very rapidly in a 2.5 Gb/s signal, so the detector and receiver have to be designed to have good high frequency response.

The levels of loss generally obtainable in a silica single-mode fiber are shown in the Figure 3-1 attenuation curve. A multimode fiber in the steady state will have slightly higher losses because the higher order (propagating) modes have energy closer to the outer edge where it is more easily lost. The term *steady state* refers to the stable propagating modal structure which is found a few meters distant from the signal launch point.

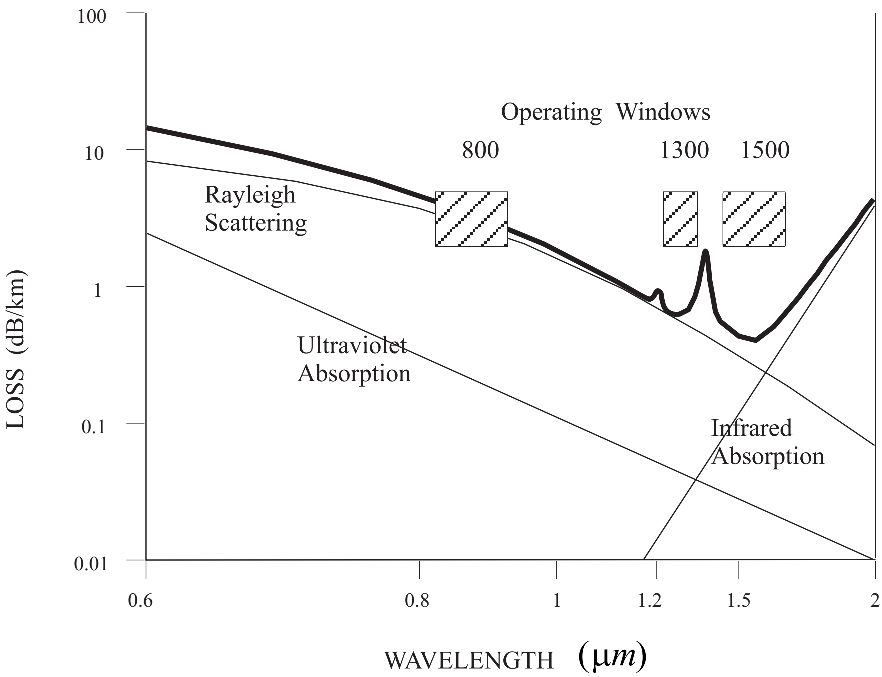

Figure 3-1 *Optical fiber attenuation (silica).*

At short wavelengths ultraviolet absorption is important but is generally overshadowed by *Rayleigh scattering*. At higher wavelengths the minimum attainable attenuations are controlled by *infrared (IR) absorption*. The "V" shaped attenuation curve that results from these two controlling factors, Rayleigh scattering and IR absorption, shows that attenuation is lowest at the relatively longer wavelengths between 1300 and 1550 nm. In Section 3.3 it will be shown that this range fortuitously coincides with the wavelengths where chromatic dispersion is minimized in Silica fibers.

Additional factors, such as impurities and bends, will also contribute to fiber attenuation but they can be minimized with good fiber and cable design, manufacture and installation. Fibers made with different materials, such as plastic, will have higher attenuations. Plastic fibers are attractive in the region of visible light where their loss is minimized. The attenuation is still much higher than that of silica.

Systems using silica fibers have a wide range of sources and detectors available to match the different types and quality of fibers. Through research there is a promise of even lower loss fibers made from materials other than glass or plastic, but the silica based fibers currently in widespread communication use give very satisfactory performance. The supporting hardware and systems that have been developed based on silica fiber use make near term obsolescence highly unlikely. The best values of attenuation for silica glass fibers are 0.15 dB/km for single-mode and 0.24 dB/km for multimode fibers, measured at 1550 nm in the trough between the Rayleigh scattering and IR absorption curves.

Three "windows" of operation for fiber systems evolved during the first two decades of silica fiber use, primarily because of the shape of the attenuation curve. These are the 800, 1300, and 1550 nm windows identified in Figure 3-1. An OH^- (water ion) energy absorption peak in silica, centered at 1390 nm, led to the separation of the two longer wavelength windows. Many devices that are used to provide optical output, detection and networking capability are available commercially for these windows. One reason these windows in glass fibers have become standard stems from the chromatic dispersion minimum for pure silica around 1300 nm (Section 3.3). With the gradual improvement in quality of single-mode fibers, it has become possible to use the whole range from 1300 to 1550 nm. In fact, this range now is described using sub-ranges much as radar systems have "bands" in the GHz range (Chapter 8).

The attenuations in Figure 3-1 should be thought of as causing a loss in level to the whole optical signal as it progresses down the fiber. Any in-band attenuation variations will not affect the intensity-modulated signal. Fiber dispersion caused by phase shift variation with wavelength will play a role, however, in amplitude performance by causing rolloff of the fiber's electrical (baseband) response. The larger the dispersion across the signal's bandwidth, the more pronounced this effect. This results in the standard fiber specification given in Mhz-km that describes a fiber's useable bandwidth.

3.2.1 *Material Absorption*

Small amounts of light will be absorbed in an optical fiber because of the chemical composition of glass. The energy is converted to heat. The fundamental mechanism causing this is the excitation of molecular modes of vibration called *resonances*. At short wavelengths, in the ultraviolet region, intrinsic absorption in silica is high due to electronic resonance around 140 nanometers. This loss contribution decreases with increasing λ following $e^{k/\lambda}$. At longer wavelengths intrinsic (IR) absorption is high around 8 µm, also due do molecular vibration, but decreases with decreasing λ following $e^{-k/\lambda}$. These fundamental material absorption characteristics shape the attenuation trough that makes silica fibers attractive. The spectral attenuation plot in Figure 3-1 shows the low wavelength, ultraviolet absorption and the high wavelength, IR absorption. The former is less of a contributor to attenuation because Rayleigh scattering effects are greater at lower wavelengths. Absorption in the IR limits the use of higher wavelengths in all silica fibers.

There are other sources of material-caused attenuation in addition to these intrinsic sources. Very early in the development of optical fiber technology it was realized that metal impurities (e.g., ions of chromium, cobalt, copper and iron) were particularly troublesome. Around 1970 the ability to drastically reduce metal ion concentrations in silica was realized (Figure 1-3). Optical fiber attenuation performance has been improving steadily. If the metal ion concentrations are kept below 1 part per billion (ppb) during the glass refining process, the losses from these impurities will be less than 1 dB/km. Modern fabrication techniques can reduce these levels to less than 0.1 ppb. Unfortunately, the non-metallic dopants needed to control the core and cladding indices of refraction act in the opposite direction and slightly increase absorption.

With metal impurities under control, the next contaminant of significance that needed to be controlled was water vapor, in the form of the OH^- ion. The fundamental water vapor absorption (resonance) takes place at 2730 nm, but significant overtones occur at 1390 nm and 1240 nm. Recall that as wavelength decreases, frequency increases. Notice the two water peaks in the spectral attenuation plot in Figure 3-1. Early commercial long wavelength, single-mode systems were designed for the two regions or windows which flank the 1390 nm peak. Concentrations of water vapor of less than 1 ppb can now be achieved by drying the glass in Chlorine gas during manufacture. This has resulted in much lower water peaks — and the ability to use the total spectrum from 1300 nm to 1600 nanometers for single-mode, long distance systems (Chapters 7, 8).

3.2.2 *Scattering Losses*

Light propagating in a fiber can be converted to unbound (radiative), and/or backscattered light. No matter how good the quality of the glass it will still contain small, molecular level irregularities, either within the glass or on the surface. The resulting minute variations in the glass's refractive index cause scattering. This attenuation phenomenon is called Rayleigh scattering, and its effect is shown in Figure 3-1. Core propagation will be only slightly affected by these irregularities as long as the wavelength of the light is large compared to the size of the imperfections. The scattering takes place in all directions. The scattered light represents a small loss of signal, but can still interfere with the performance of advanced high-speed systems. The energy of the scattered light is proportional to $1/\lambda^4$.

An important use of Rayleigh scattering is found in the *Optical Time Domain Reflectometer (OTDR)*. In the OTDR, light energy sent by a transmitter will be reflected back by reflections and Rayleigh scattering. The reflections help locate fiber link imperfections and the scattered light gives a measure of overall fiber attenuation. The OTDR is discussed more thoroughly in Chapter 7.

3.2.3 *Bending Losses*

Bends in a fiber can lead to increased loss. Large scale bends have radii greater than the diameter of the fiber and are called *macrobends*. Macrobends are caused by the pulling, squeezing, or bending of the fiber/cable during spooling or during installation. They can generally be seen from outside the cable. Macroscopic fiber bends of 10 cm or more will cause very little bending loss. If a 125 micron diameter fiber is bent to a radius of a few centimeters, however, there will be bending losses as well as the possibility of extreme stress and breakage. The stress and possible damage may not show immediately, which is the reason for exercising care during installation.

Microbends are a continuous succession of very small bends resulting from a number of causes: non-uniformity at the cladding/coating interface; non-uniform lateral pressures from the cabling process: microscopic variations in the location of the core axis. These cannot be seen from outside the cable. Their equivalent radii of curvature are a few millimeters. Microbend losses arise as the fiber is slightly distorted when undergoing spooling or installation. Light rays traveling near the critical angle will lose energy at the irregular interface between the cladding and buffer. In multimode fibers energy will also be coupled, and lost, from the guided modes to the leaky or non-guided modes. These losses can be minimized in fiber/cable manufacturing. Microbend losses are less serious in a loose tube constructed cable, or in a tight-buffered fiber that has a soft, flexible external covering (Chapter 2).

3.3 Dispersion (Arrival Time Distortion)

The other main parameter determining optical fiber system performance is arrival time distortion at the detector. The components in a fiber system each contribute to dispersing or spreading out the signal energy over time as it travels. *Dispersion* is defined as a spreading in time of arrival of a received signal beyond its original time spread. A system designed according to time of arrival distortions caused by dispersion is referred to as being *bandwidth* or *rise time limited*. In Chapter 7 dispersion will be directly related to available bandwidth/pulse rise time and, hence, total system performance. The fiber will generally be the greatest contributor to total system dispersion.

In the current generation of optical systems, where only intensity (power) is modulated and detected, the effects of in-band phase distortion can be neglected. Phase distortion will cause non-constant group velocity, however, which results in arrival time distortion. Consider, for example, a pulse train generated using a laser and transmitted on a fiber with arrival time distortion. Figure 3-2A illustrates what happens as pulses spread, interfere with each other, and lose amplitude as a result of the spread in arrival times of the constituent wavelengths.. The spreading has the same effect on the signal as in-band amplitude distortions have on radio signals; the baseband signal spectrum suffers roll-off. This interference and pulse distortion can be significant in some fiber systems, particularly those with long lengths of fiber. The parameter $\Delta\tau$ is used to describe the time spread beyond the undistorted time of arrival of the input signal.

Figure 3-2B illustrates how dispersion results in pulse spreading. At the time of the initial pulse each of the source's wavelengths will be modulated by the input signal. Some wavelengths will carry decreased power because the source has unequal power distributed across its output spectrum. At a later time, after travel down the fiber, λ_2 arrives ahead of λ_1. The pulse has been spread by the amount $\Delta\tau = \tau_2 - \tau_1$. A pulse's width is described by its Full-Width-Half-Max (FWHM) values in time, τ_1 and τ_2 for the initial and spread pulses respectively.

Note that this diminished received pulse amplitude is caused by dispersion alone, not by in-band amplitude distortions. In the next Section, $\Delta\tau$ will be directly related to a fiber's 3 dB bandwidth. Since the effects of dispersion on a signal are dependent on fiber length, an important measure of a fiber's quality is the bandwidth-distance product. A fiber with a specified bandwidth-distance product of 500 MHz-km, for example, would have a useable bandwidth of 500 MHz over a one km distance and 250 MHz over a two km distance. The specified frequency is at the 3 dB rolloff point on the amplitude response curve. The type of transmitted signal would dictate the required bandwidth, and thus the maximum distance available from a

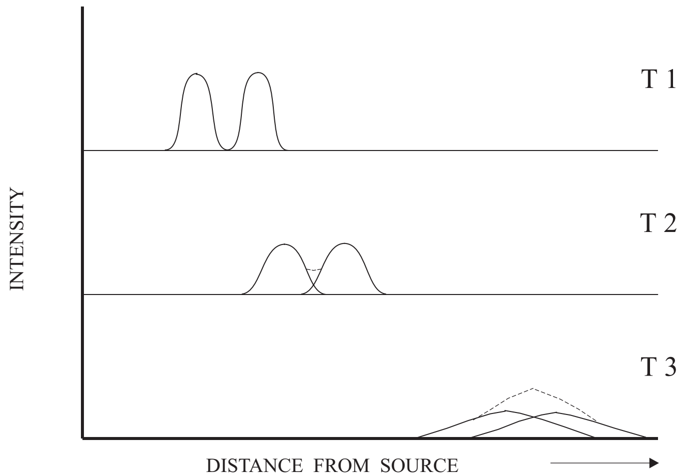

Figure 3-2A *Pulse spreading with distance.*

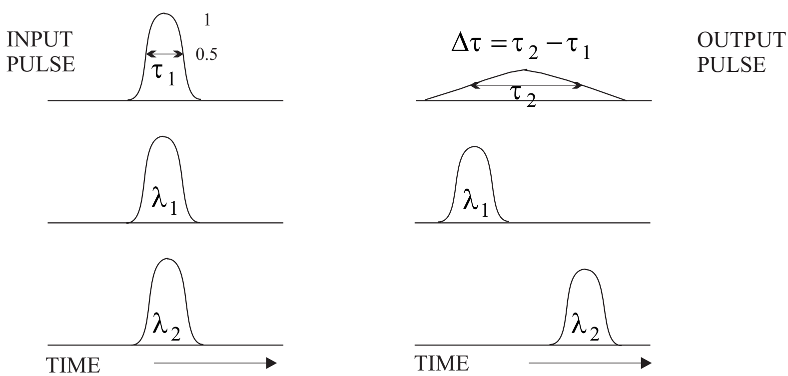

Figure 3-2B *Pulse spreading with wavelength.*

given fiber. The bandwidth-distance product of single-mode fibers is much higher than that of multimode fibers.

In a multimode fiber many hundreds of modes will be present when the signal is propagating in the steady state. The dominant cause of arrival time distortion in multimode fibers is *modal dispersion* (sometimes called *intermodal dispersion*), which is the spread in arrival times of these modes. Single-mode fibers propagate only the fundamental mode and do not have modal dispersion. Single-mode fibers have two other forms of dispersion that become dominant, however, material and waveguide dispersion. When combined they are called *chromatic dispersion* (sometimes called *intramodal dispersion*). These two contributors are present in multimode fibers, but usually make minor contributions relative to modal dispersion. The effects on the signal of chromatic dispersion are proportional to source linewidth. Modal dispersion effects are not dependent on source linewidth.

3.3.1 *Delay, Bandwidth, and Risetime*

This section discusses the impact of time-of-arrival distortions ($\Delta\tau$) caused by fiber dispersion. The time-of-arrival distortion is then related to the more useful measures of fiber equivalent bandwidth and rise time. Rise time and bandwidth estimates are interchangeable when components are assumed to have a first-order rolloff response at high baseband frequencies. The bandwidth/rise time performances of the optical source and detector are quantified in Chapters 4, 5 respectively. They are combined with the fiber's rise time estimate in Chapter 7 to obtain total system performance.

The next Section quantifies the dispersion generated in the two main types of silica fibers. It might appear that this sequence puts the cart before the horse, but first understanding how pulse spreading relates to bandwidth and rise time will make it easier to understand the impact of fiber dispersion.

The three main system elements (source, fiber, detector) each contribute to time-of-arrival distortion. The fiber will be the largest contributor. A four-step process is followed in analyzing the effect of time delay distortions on the signal:

- Estimate the total delay spread, $\Delta\tau$, in the arrival time of the constituent wavelengths in the intensity modulated signal
- Derive the 3 dB fiber bandwidth from this time spread
- Derive an estimate of the rise time of the fiber from the fiber's bandwidth
- Combine the fiber rise time with the source and detector rise times to derive total system rise-time performance.

The fourth step is covered in Chapter 7. Although rise times are associated with digital system pulses, this approach is also useful in estimating analog system performance.

Another approach, used when a more exact analysis of digital system performance might be needed, considers the root mean square (RMS) spreading of an impulse. The fiber's bandwidth is determined from the Fourier transform of the fiber impulse response (the $H(\omega)$ transfer function in Equation 3.1). The source and detector will also have impulse responses. Their impulse responses will be either measured or assumed. Because the source, fiber, and detector are initially assumed to have linear transfer functions, their impulse responses can be cascaded. The resulting total pulse spread relative to the input pulse will give the system performance. In both the delay time approach used in this book and the impulse response approach, the time spreading contributions of the three major system components are combined on a root-sum-square (rss) basis when determining total system performance.

Returning to the delay distortion or time-of-arrival-spread approach, the first step is to find the delay difference, $\Delta\tau$, caused by fiber dispersion. Note that the leading and trailing edges of the input pulse in Figure 3-2B are spread in their time of arrival by $\Delta\tau$. All wavelengths within the source linewidth are transmitting at the time of occurrence of the leading and trailing pulse edges. The differing delays between the wavelengths caused by dispersion will cause the arrival times of these edges to spread. The same spreading happens throughout the pulse, of course, but focusing on the edges gives a clearer understanding of the phenomena. This time-of-arrival analysis has to assume that the source spectrum is constant. This is a reasonable assumption when analyzing the effects of fiber dispersion, even though on an instantaneous basis optical semiconductor sources are not stable. In particular, at turn-on and turn-off they present unique noise problems called mode partitioning and chirp (Chapter 4).

The fiber's delay difference, $\Delta\tau$, must first be translated into a 3 dB rolloff frequency. Consider a simple sine wave modulating an optical source. The source has a wide range of wavelengths in its linewidth. As a result, the sine wave modulates all wavelengths at the same instant. Two wavelengths, one on the spectrum high side and the other on the low side, will arrive at the receiver at different times because of fiber dispersion. At some delay, these two small contributors will be detected out of phase with each other. If the delay difference between the wavelengths is equal to ½ the modulating frequency's period, the contribution from these two wavelengths to the demodulated signal will cancel. This results in a rolloff in the bandwidth performance of the fiber. The frequency corresponding to this delay difference is used as an approximation of the fiber's 3 dB bandwidth:

$$f_{3-dB}(optical) = \frac{1}{T_{3-dB}(optical)} = \frac{1}{2 \times \Delta\tau} \qquad 3.2$$

where $\Delta\tau$ is the delay between the highest and lowest wavelength in the source's linewidth.

In electronic communications, bandwidth is stated in terms of a 3 dB or half power point on a curve that plots amplitude vertically and frequency or wavelength horizontally. The degree of rolloff at the high frequencies can be steep or gradual. The most gradual rolloff is caused by a *first-order response*. A first-order response in a component is sometimes modeled by a resistor/capacitor (RC) low pass filter combination. For simplicity in this book's analyses, first-order responses will be used for all components where high-frequency bandwidth shape has to be considered.

Sources, fibers, and detectors all have ½ power bandwidths in their baseband responses. The optical detector converts optical input power directly into an electrical output current that replicates the baseband signal input to the transmitter. At the fiber's 3 dB optical frequency the demodulated signal will be down 6 dB since the power in the detector output depends on the square of the current. As a result, a fiber's electrical or baseband 3 dB frequency and its optical 3 dB frequency are related by:

$$f_{3-dB}(electrical) = \frac{f_{3-dB}(optical)}{\sqrt{2}} = 0.707\, f_{3-dB}(optical) \qquad 3.3$$

In fibers, the optical bandwidth is greater than the electrical bandwidth that is realized after demodulation. Manufacturer's specifications should be read carefully to determine which bandwidth is being presented. Usually the bandwidth given in fiber bandwidth-distance product specifications is the larger optical bandwidth. The detector alone will have a specified risetime that generally includes the effects of its associated circuitry.

A system or component that is modeled as first-order will have the following relationship between electrical bandwidth and rise time:

$$f_{3-dB}(electrical) = \frac{0.35}{t_r} \qquad 3.4$$

For purposes of simplifying the relationships between bandwidths and risetimes, the fiber is assumed to have this type of response. For a NRZ coded digital system (Chapter 7), and assuming that the received pulses have an (equal) exponential rise and fall caused by this first-order rolloff, the time delay relates to the bandwidth and rise/fall times by:

$$\Delta\tau = \frac{1}{2 \times f_{3-dB}(optical)} = \frac{1}{2 \times \sqrt{2} \times f_{3-dB}(electrical)} = t_r \qquad 3.5$$

A non-return-to-zero (NRZ) coded signal uses a pulse length equal to the bit-rate.

As an example in applying these relationships, assume a GMM fiber with a 200 MHz-km (optical) performance specification. In a 2 km link the delay spread/rise time contribution from the fiber alone for NRZ pulses would be:

$$t_r = \Delta\tau = \frac{1}{2 \times \dfrac{200Mhz - km}{2km}} = 5ns$$

A source will have its risetime and/or 3 dB baseband response frequency specified by the manufacturer. If only one is given, the other can be derived by assuming a first-order response and applying Equation 3.4. Usually the specification will include the bandwidth limitations of the electronic drive circuitry packaged with the source.

The time delay distortions caused by chromatic dispersion in the fiber are a function of the source's linewidth. The time average output spectrum of an optical source can be modeled as a central wavelength with ½ power or 3 dB wavelengths on either side. The wavelength difference between these two ½ power wavelengths is specified as the source's linewidth. The term *Full-Width-Half-Max (FWHM)* is used to describe this ½ power bandwidth. In addition to the source's linewidth, the average center wavelength and power must also be specified. All of these are needed in analyzing the performance of a system.

3.3.2 *Modal Dispersion,* $\Delta\tau_{\mathbf{mod}}$

In multimode fibers the spread in energy arrival times is caused primarily by the differing modal propagation speeds (Chapter 2). This type of time distortion is referred to as modal dispersion, also called intermodal dispersion. The modes travel with different angles of ray incidence, which results in different path lengths and arrival times at the optical detector. A GMM fiber has better modal dispersion performance than a step-index fiber because the range of modal speeds is decreased.

Each mode in a multimode fiber travels at its own average group velocity. In a step-index fiber the ray traveling directly down the fiber's core will arrive at the detector in the time:

$$\tau = \frac{L}{\nu}, \text{ where } L = \text{fiber length}, \ \nu = \text{core velocity} = \frac{c}{\eta_1} \qquad 3.6$$

A meridional ray, describing the highest order propagating mode group, will travel at the critical angle, ϕ_c, and arrive at a greater time:

$$\tau_c = \frac{L}{\nu\,(\sin\phi_c)} \qquad 3.7$$

The total modal pulse spread for the step-index, multimode fiber can then be estimated at:

$$\Delta\tau_{\text{mod}} = \tau_c - \tau = \frac{L}{\nu \sin\phi_c} - \frac{L}{\nu} = \frac{L}{\nu}\left[\frac{1}{\sin\phi_c} - 1\right] = \frac{L\eta_1\Delta}{c} = \frac{(NA^2)L}{2\eta_1 c} \qquad 3.8$$

Where, from Equation 2.2:

$$\Delta = \frac{\eta_1 - \eta_2}{\eta_1} \approx \frac{\eta_1 - \eta_2}{\eta_2} = \text{Fractional index of refraction}$$

The derivation above is one of the simplest used to arrive at step-index modal spread, but is also one of the easiest to visualize. A more accurate analysis would use the effective indices of refraction for the propagating mode groups instead of the core and cladding indices, but the results would be quite similar. In an application of Equation 3.8, assume a step-index fiber with $\eta_1 = 1.5$, $NA = 0.173$m, $\Delta = 0.007$. The modal time spread per unit length becomes:

$$\frac{\Delta\tau_{\mathrm{mod}}}{L} = \text{step - index modal time spread per unit length} = 34\ ns/km$$

This seems like a small delay, but consider transmitting a 20 Mb/s RZ signal on this fiber. In return-to-zero coding each pulse is generally ½ of a bit period. Pulses at the fiber input are separated by 50 ns but after about 1 km the leading and trailing edges can be viewed as spreading 34 ns, thus resulting in mutual interference. Pulses would overlap and could not be reliably detected, as pictured in Figure 3-2A. Maximum signaling rates based solely on fiber-induced delay distortion are discussed later in this Chapter. Maximum signaling rates based on total system delay distortion are discussed in Chapter 7.

In graded index (GRIN) multimode fibers, GMM, higher order rays (modes) are bent gradually back to the axis as they progress down the fiber. During a large portion of their travel time, they are close to the cladding in a region of low refractive index and higher velocity. As a result, in GMM fibers the average velocity for these modes will be higher and closer to that of the axial, fundamental mode. Another way to view this effect is that rays crossing the axis at an angle at the same time will tend to arrive at the next axial zero crossing with approximately the same delay and hence suffer less travel time distortion. The spread in modal arrival times is about 100 to 1000 times better in a GRIN fiber compared to a step-index multimode fiber.

For a GMM fiber with a core refractive index shape that is parabolic (Equation 2.17), the theoretical modal time spread per unit length is given by (without derivation):

$$\frac{\Delta\tau_{\mathrm{mod}}}{L} = \frac{\eta_1 \Delta^2}{8c} \qquad 3.9$$

Using the same parameter values as in the step-index example above, the modal time spread per unit length would be:

$$\frac{\Delta\tau_{\mathrm{mod}}}{L} = 30.6\ ps/km$$

The fractional index, Δ, in a GMM fiber is derived using the refractive index at the axis relative to the cladding index. Note that the modal dispersion in this GMM fiber is about 1000 times better than that of the step-index fiber example.

3.3.3 *Chromatic Dispersion,* $\Delta\tau_{chr}$

Single-mode fibers do not have modal dispersion but still have arrival time distortions. From Chapter 2, the index of refraction of the material in the glass is not a constant for all wavelengths. Since the group velocity, which is the velocity of energy propagation in the fiber, is a function of the index, the different wavelengths in an optical signal will travel at different velocities. Optical sources for low-speed/low-bandwidth fiber systems are essentially non-coherent and, hence, generate a relatively large range of wavelengths in their linewidths.

Consider the intensity of a laser pulse that is transmitted down a glass fiber in the fundamental mode alone. Different wavelengths in the pulse will not arrive at the same time, which leads to chromatic dispersion (also called intramodal dispersion). Chromatic dispersion is made up of two components, *material dispersion* and *waveguide dispersion*. Material dispersion is caused by the variation of the core's index of refraction with wavelength. As might be suspected, an expected amount of material dispersion has to be accepted once the core doping has been determined. Waveguide dispersion, which is the smaller of the two arrival time distortions, is caused by variations in the profile or cross-section of the core's index of refraction. Sometimes the cladding profile is also varied to help control waveguide dispersion. Chromatic dispersion is controlled in single-mode fibers by using the waveguide core/cladding profile to control the waveguide dispersion. The material dispersion component can be effectively cancelled at one or more wavelengths. The two components are actually somewhat interrelated, but analyzing them separately and adding their effects gives a good approximation to the total amount of chromatic dispersion:

$$D = \text{Total Chromatic Dispersion in } \frac{ps}{nm \cdot km} = D_{mat} + D_{wag} \qquad 3.10$$

In this discussion, chromatic dispersion will be calculated only for the fundamental mode, even though each mode group (in a multimode fiber) experiences some chromatic dispersion. In multimode fibers modal dispersion predominates. Analyzing the combined effects is too complicated for this book. Further, recall that the applications of optical fibers in communications today have separated into two main areas: short distance, medium bandwidth local networks using multimode fibers, and long distance, high capacity networks using single-mode fibers. If the system designs are dispersion limited, the former will be controlled by modal dispersion and the latter will be controlled by the fundamental mode's chromatic dispersion.

An exception occurs when a GRIN high bandwidth multimode fiber is used at 800 nm with a wideband (LED) source. In this case the chromatic dispersion becomes an important consideration because the source has a broad linewidth and chromatic dispersion is high in silica at 800 nm. An approximation to the combined effect of modal and chromatic dispersion is derived for this case by adding their time spreads on an rss basis.

Material dispersion occurs because the index of refraction of Silica is not constant, or a linear function of optical wavelength. Figure 3-3 shows the index of refraction of Silica and the group index/velocity as a function of wavelength. Note that the first-order derivative of the material index is zero and the group velocity is flat around 1300 nm. In this region, group velocity and material dispersion have little dependency on wavelength. Also note in Figure 3-3 how the bulk index curve is shifted by the addition of 13.5% Germanium doping. This illustrates one of the two main ways chromatic dispersion is controlled, the other being by the control of waveguide dispersion through the careful design of the refractive index profile.

The group velocity, ν_g, is the speed of propagation of energy in the fiber. The propagating signal in the fiber will experience a corresponding effective group index of refraction, η_g, derived from the group velocity. The group velocity is equal to:

$$\nu_g = \frac{c}{\eta_g} \tag{3.11}$$

Where, without detailed derivation:

$$\eta_g = \eta_1 - \lambda \frac{d\eta_1}{d\lambda} \tag{3.12}$$

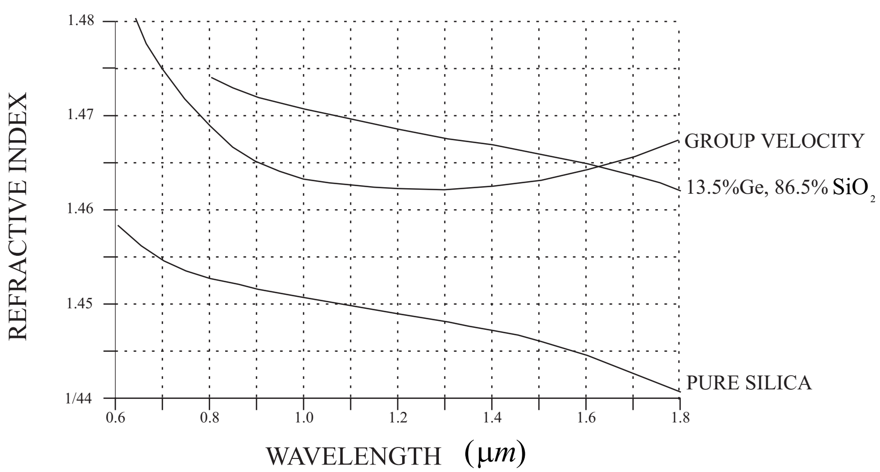

Figure 3-3 *Indices of refraction (silica).*

A more exact analysis would use the modal effective index of refraction instead of the core index, but the approach used here will suffice, particularly since it will be applied exclusively to the analysis of single-mode fibers.

The average arrival time, τ, of light transmitted over a length, L, of fiber is given by:

$$\tau = \frac{L}{v_g} = \frac{L}{c}\left(\eta_1(\lambda) - \frac{\lambda d\eta_1(\lambda)}{d\lambda}\right) \qquad 3.13$$

The pulse time spread, $\Delta\tau_{mat}$, due to a source having a linewidth, $\Delta\lambda$, then becomes:

$$\frac{\Delta\tau_{mat}}{\Delta\lambda} = \frac{d\tau}{d\lambda} = -\frac{L\lambda}{c}\frac{d^2\eta_1}{\delta\lambda^2} = -LD_{mat} \quad \text{where} \qquad 3.14$$

$$D_{mat} = \text{material dispersion coefficient} = \frac{\lambda}{c}\left(\frac{d^2\,\eta_1}{d\lambda^2}\right) \text{ in } \frac{ps}{nm \cdot km} \qquad 3\text{-}15$$

The material dispersion coefficient is plotted in Figure 3-4 for pure Silica and Silica doped with 13.5% Germanium. Material dispersion is large at 800 nm, and drops to approximately zero in the region of 1200 to 1400 nm, depending on the Ge content. The zero point is determined by where the second order derivative of the refractive index in Equation 3.14 becomes zero. In the 1550 nm window the material dispersion is negative,

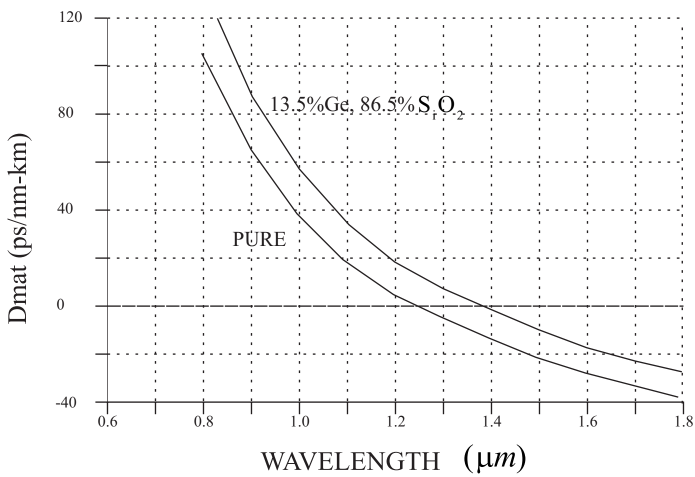

Figure 3-4 *Material dispersion coefficients (silica).*

or opposite in sign. The change in sign means that on the left side of the zero wavelength the (lower) wavelengths in a signal linewidth will be delayed more than the higher wavelengths. On the right side of the zero crossing the situation is reversed, the higher wavelengths will be delayed more. For the discussion here, the differences in delay times are the important factor, not the absolute relationship between wavelength delays. Soliton transmission, discussed later in Chapter 7, will make use of these relative delays. In some presentations of material dispersion the curves will be reversed because the minus sign in Equation 3.14 is dropped.

The effects of chromatic dispersion on a transmitted signal are directly dependent on the center wavelength of the signal and the linewidth of the source. At first window wavelengths around 800 nm, material dispersion dominates and the contribution of waveguide dispersion is small and usually neglected. From 1300 to 1550 nm the two are equally important. The amount and shape of the waveguide dispersion curve is controlled by the size and shape of the core, the smaller the core the greater the effect. This control allows the optimized single-mode fiber designs described in Chapter 2. These optimized core designs have become important in realizing Terabit/sec transmission systems (Chapter 8).

Waveguide dispersion depends on the ratio of the fiber's core radius to the signal wavelength. A detailed mathematical analysis of this dispersion component is beyond our intent, but it is constructive to examine what can be achieved through its control. The solid lines in Figure 3–5 plot the waveguide dispersion factor, D_{wag}, for a step-index single mode fiber with different core radii. The so-called conventional SM fiber has a core radius, a, of 4.5 µm, 4% Ge core doping and a pure Silica cladding. The Germanium doping plus the waveguide dispersion shifts the zero dispersion wavelength from 1270 for pure Silica to 1308 nm. Note how the waveguide dispersion component increases with decreased core radius. If the radius is reduced further to 1.8 µm, the zero would be shifted all the way out to 1750 nm, but this would make the mode field very small and hurt coupling at splices and connectors. A related parameter, the naturalized frequency V (Chapter 2), must be kept between 1.5 and 2.4 to keep the fundamental mode energy bound to the core. Recall that the cutoff wavelength occurs when V equals 2.4. Since the ratio a/λ is a prime determinant of V, reducing the radius reduces V which results in increased susceptibility to higher order mode conversion at discontinuities because of increased cladding energy.

The dotted lines in Figure 3-5 show the total chromatic dispersion, $D_{mat} + D_{wag}$, for three single-mode fiber types: conventional step-index, dispersion shifted, and dispersion flattened. The curves represent general results, but they indicate that a great deal of chromatic dispersion control is possible by controlling the waveguide dispersion component. Control is achieved through variation of indices of refraction, depth and width of cladding par-

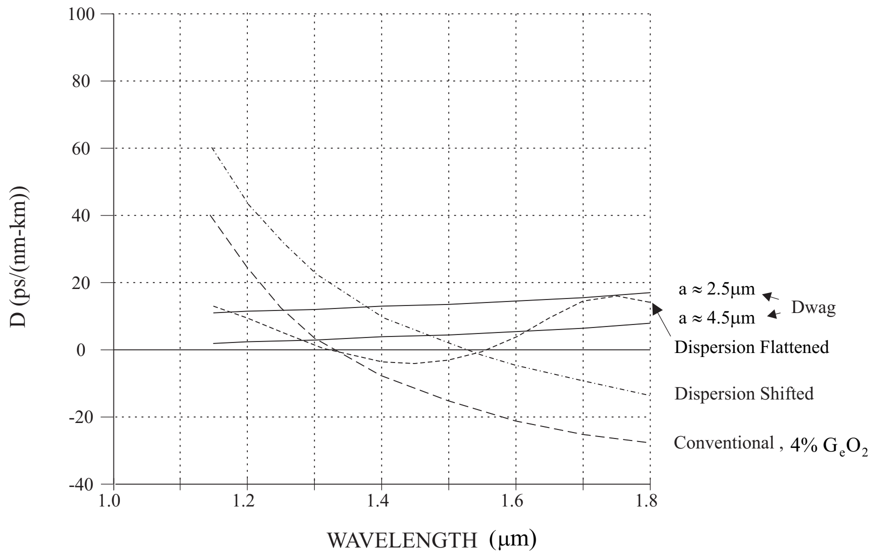

Figure 3-5 *Total dispersion-single mode fibers.*

titions, core shape, and doping concentrations. This control of the waveguide dispersion factor, coupled with constantly improving manufacturing techniques, has resulted in the many applications of single-mode fiber seen today. Achieving low dispersion over a wide band translates directly into high system capacities and long distances between regenerators.

With the dispersion-shifted fiber, the objective is to realize a dispersion zero in the 1550 nm region. The core profile in Figure 2-12 shows that this is achieved by using the combination of lower Ge core doping, a depressed cladding using Fluorine doping, and a trapezoidal shaped core. The lower Ge content helps reduce attenuation and the trapezoidal shape helps confine the mode field. In general, these fibers have core radii between 2 and 2.5 μm, core doping of up to 13% Ge, and index differences between 0.6 and 1.8 %.

Finally, a representative curve for a dispersion-flattened fiber is plotted. An index profile for this fiber is also shown in Figure 2-12. Because of the profile this fiber is also called double or "W" cladding. Trying to use step-index designs to achieve flattening leads to unacceptably high attenuations because the Ge doping is excessive. Figure 3-5 illustrates the degree of control of the chromatic dispersion characteristics of single-mode fibers. Building on Equation 3–14, we can now state $\Delta\tau_{chr}$ for a single-mode fiber:

$$\Delta\tau_{chr} = \Delta\lambda(L(D_{mat} + D_{wag})) = -\Delta\lambda LD \qquad 3.16$$

As an example of the application of Equation 3.16, consider a laser diode centered at 1550 nm with a linewidth of 0.1 nm transmitting a signal over 1 km of the conventional SM fiber whose dispersion is plotted in Figure 3-5. The *D* value is approximately –17 ps/(nm-km) which results in:

$$\Delta\tau_{chr} = 0.1(1)(-17(10^{-12}) = -1.7\ ps/km$$

Comparing this with the result of 30 ps/km for the GMM fiber example shows the single-mode fiber to be about 20 times better in arrival time distortion. If a dispersion-flattened or shifted fiber had been chosen, the single-mode fiber would be even better. Note also from Section 3.2 that a single-mode fiber will have slightly better attenuation performance than a multimode fiber. The significance of these improvements in terms of faster bit rates and longer distance transmission is discussed in Chapters 7, 8.

3.4 Polarization

Single-mode fibers have improved significantly in quality, uniformity and bandwidth-distance performance through the last two decades. The chromatic dispersion improvements discussed in the preceding section now allow greatly increased system lengths and capacities. A problem that emerges as these fibers are pushed to their performance limits is polarization mode dispersion (PMD). Depending on the quality and care in the manufacturing and cabling stages, this arrival time distortion can vary from less than 0.05 ps/$\sqrt{\text{km}}$ to several ns/$\sqrt{\text{km}}$ in conventional single-mode fiber. PMD is not a problem in multimode fiber.

From Equation 3.2, considering polarization mode dispersion only, PMD would allow a usable bandwidth for intensity-modulated systems of 50 GHz over 200 km when it is low, but only 500 MHz/km when it is high. Current systems are approaching 40 Gb/s speeds and therefore require high quality fiber to keep polarization mode dispersion low.

In Chapter 2 it was pointed out that each propagating mode in a nominally circular optical fiber actually has two polarizations. Recall that an electromagnetic wave's polarization is determined by the linear direction of its E-field, which may be stable or changing. The energy in the two polarizations becomes coupled in conventional fiber because of the fiber's unavoidable imperfections and strains. The better the quality of the fiber and cable, the closer together the two modes are to having equal transmission characteristics, and the lower the value of PMD dispersion.

PMD in conventional fibers results in an elliptically polarized wave at the detector that changes orientation and amplitude with wavelength and time. This ellipticity is caused by the two orthogonally polarized modes having different propagation characteristics and, hence, group velocities. Differential transmission for two orthogonally polarized modes is called *birefringence*. With intensity-modulated systems this causes dispersion. In coherent systems, where the receiver must have an incoming carrier with known polarization, the signal cannot be detected. Examples of coherent optical systems or sub-systems are optical gyroscopes/sensors, integrated optical circuits, and coherent transmission systems. These are all discussed in later chapters. Polarization can be maintained and used for these applications only in single-mode fibers..

Special fibers, called *polarization maintaining fibers (PMF),* can be constructed so that their internal propagation characteristics either decouple the two modes or suppress one of them. In a linearly birefringent fiber, energy with an E-field orientation in one of the directions is not coupled into the other, and a signal with one of the polarizations will transfer very little energy into the other polarization. In a truly single-polarization fiber one of the two modes is attenuated. Both of these PMF fibers preserve the polarization of the launched signal at the detector. If an arbitrarily polarized signal is input, only one polarization will immerge.

Both types of PMF fibers are manufactured by either of two methods: inducing asymmetric internal stresses, or changing the internal geometry of the fiber through added layers of differently doped glass. Figure 3-6 gives profiles of fibers intended to control birefringence by these two methods. These fibers would be used only for signals that require maintenance of a state of polarization. They would not be used for regular intensity modulated signals because the PMD would be significant. Figure 3-6A shows a fiber with an elliptically deformed core. By deliberately destroying the circular symmetry through built in stress on the core, the two polarizations will have decreased coupling. Boron doping is used to reduce the refractive index of Silica. The different materials have different thermal expansion characteristics so that stresses are left in the glass after cooling. One polarization will stay relatively independent of the other. It is also possible to build this type of fiber by stressing the cladding while keeping the core circular.

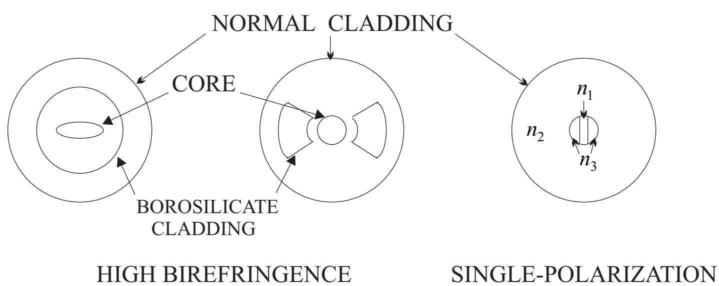

Figure 3-6 *Linear-polarization-maintaining (single-mode silica).*

Figure 3-6B illustrates a “Panda” or “bow-tie” fiber also constructed by introducing high stress regions during manufacture. This fiber construction can be used to make either a high birefringent or single-polarization fiber. One advantage of this approach is that attenuation is lower if the stressed region is displaced from the core.

Figure 3–6C shows the cross section of a single-polarization fiber. This is called a *side-tunnel* or *side-pit fiber*. This fiber’s core has asymmetrical indices of refraction; a core of 1.47, a cladding of 1.46, and the side-pit of 1.45. Energy is suppressed in one of the modes because its cutoff wavelength has been separated from the main mode. Remember that in a circularly symmetric fiber, theoretically, the fundamental mode (and its orthogonal twin) do not have a cutoff.

3.5 Non-Silica Fibers

Silica fiber manufacturing and use have matured significantly. Silica fibers now are very economical and give excellent performance in many different applications. As a result, there is not a great deal of emphasis being placed on finding alternative fiber types for telecommunications applications. This section briefly discusses the general direction of research on non-Silica glass fibers, and what advances might be made in the future. Also, plastic optical fibers (POF) are discussed in some detail because they have unique properties that Silica cannot match. A combination of Silica and plastic has found use in plastic coated Silica fibers (PCS).

Research continues on materials and waveguide structures that offer the prospect of extremely low losses in the mid-infrared region (2–5 microns). We think of “glass” as the common window type glass we look through, and which also yields Silica fibers when purified. A promising type of glass for low-loss fibers is made primarily of heavy metal fluorides and zirconium fluoride. The basic challenge is to find a manufacturing approach that overcomes absorption and scattering. Also, long lengths of fibers with controlled profiles, structure and cabling must be realized. Dispersion can be controlled to levels less than 1 ps/nm-km. Probably the biggest barrier to their use lies in the lack of inexpensive components at IR wavelengths.

Plastic optical fibers (POF) are truly optical in the human sense of the word. They have their lowest attenuation, and hence most of their application, in the visible spectrum around 600 nm. The core is generally large, step-index, and made of *polymethyl methacrylate* (*PMMA*). A typical core size is 1000 microns. All-plastic fibers are multimode because of their large cores. The cladding is also plastic but not as thick on a relative basis as Silica fiber cladding. Index differences are high, leading to large numerical apertures and acceptance angles. Plastic fibers are used for short distance, very low bandwidth communications, as light pipes, and to transfer images. The automobile industry uses plastic fiber for the latter two applications, primarily because of their low weight and environmental robustness. For image transmission over short distances many smaller plastic fibers are combined into a bundle. Special plastic fibers are used in physician's endoscopes because of the need to transmit the complete visible spectrum.