Microbending: Its Origin and Sensitivity

Apart from the microbending loss stemming from the manufacturing process, there is, unfortunately, another cause of this problem: mechanical stress applied directly on a fiber that results in microconvexities, or microdents. This stress might occur during the cabling process—that is, when wrapping a bare fiber into protective layers, thus making a fiber cable. Thermal stress can also result in fiber microbending. And, of course, a user should be careful during installation and maintenance.

To determine the fiber's sensitivity to microbending loss from external sources, microbending tests can be performed. For example, one company winds the fiber, covered with sandpaper, over a drum and applies a calibrated force to the sandpaper. The test enables the user to compare quantitatively different types of optical fibers.

The critical component of an optical fiber that determines its microbending sensitivity is its coating. The technology exists today to produce excellent coatings, which yield substantial improvement in this fiber characteristic. (More about coatings is found in Section 7.1.)

well developed today that microbending loss is not a major problem. Optical-fiber data sheets usually do not even specify microbending loss and so you can assume it is included in the total attenuation specified.

What users can do to reduce macro- and microbending loss is to be sure to handle optical fibers with care, particularly the less-sheathed ribbon fibers, and always remember that the fiber is a very fragile medium. Mechanical and environmental stresses might change the optical properties of a fiber, resulting in deterioration of the transmitting signal.

Scattering

Suppose there is an imperfection in a core material, as shown in Figure 3.7. A beam propagating at the critical angle or less will change direction after it meets the obstacle. In other words, light will be scattered. This scattering effect prevents attainment of total internal reflection at the core-cladding boundary, resulting in a power loss since some light will pass out of the core. This is the basic mechanism underlying scattering loss.

You might wonder what core imperfections we're referring to and whether some mechanical particles might be found inside the core. A fiber core's diameter can be as small as units of a micrometer, so, knowing this, you can imagine how fine and clean the fiber-optic manufacturing process must be. This is truly one of the prominent achievements of modern technology. Therefore, you can rest assured that absolutely no foreign particles will be found inside the perfectly transparent core of an optical fiber. What might be found there, however, are slight variations in the refractive index.

Even very small changes in the value of the core's refractive index will be seen by a traveling beam as an optical obstacle and this obstacle will change the direction of the original beam. This effect will inhibit attainment of the condition of total internal reflection at the core-cladding boundary, as shown in Figure 3.7. The upshot, as noted above, will be scattering loss—light leaving the core.

Can we overcome the problem? Only by making better optical fibers. In fact, manufacturers today fabricate fiber of such a high quality that scattering loss is not a problem users

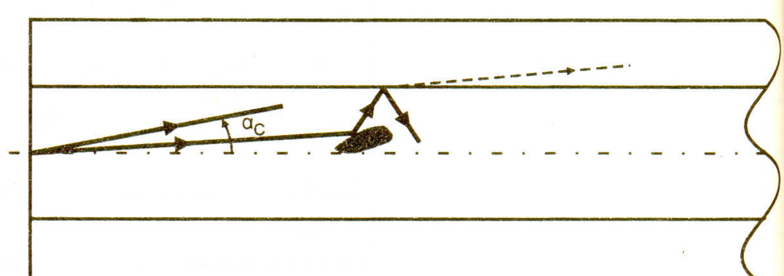


Figure 3.7 Scattering loss.

need worry about. As is the case with microbending loss, manufacturers' optical-fiber data sheets do not include any specifications on scattering loss. This type of loss is simply included in the total attenuation reported. Incidentally, this type of scattering is called Rayleigh scattering.

Note: As you have by now discerned, bending and scattering losses are caused by violation of the condition of total internal reflection. An important point to emphasize one more time is this: Light that *initially* meets the total-internal-reflection requirement might violate this condition when the fiber is bent or its core's refractive index varies.

Absorption

Basic mechanism You will recall from Chapter 2, that *if an incoming photon has such a frequency* (f) *that its energy ($Ep = hf$) is equal to the energy gap (ΔE) of the material, this photon will be absorbed by the material.* ΔE is the energy difference between two energy levels. Refer to Figure 2.10. Remember, too, that we learned that we cannot change the energy levels of the material, since they have been predetermined by nature. What we can do, though, to reduce or eliminate absorption is change either the light frequency, f, or work with another material. Remember that changing the light frequency, f, means also changing the light wavelength, λ, since $\lambda f = c$, where c is the speed of light in a vacuum.

Now imagine that light (which, you'll recall, is a stream of photons) travels down an optical fiber and encounters a material whose energy level gap is exactly equal to the energy of these photons. Obviously, this impact will lead to light absorption, resulting in a loss of light power. This is the basic mechanism of the third major reason for attenuation in optical fibers.

Does this type of attenuation depend on light wavelength? It follows directly from the above explanations that it does. In other words, there is a spectral dependence of absorption, as shown in Figure 3.8.

We now need to ascertain whether a bulk core material, like silica, absorbs light. Optical fiber, as we've seen, is a transparent strand, that is, a "nonabsorptive" material. Manufacturers make every effort to make their bulk core material as transparent to light as possible. Absorption properties that still remain are caused not by silica atoms but by some molecules of the hydroxide anion OH^-, often called high water. These molecules are incorporated in silica during the

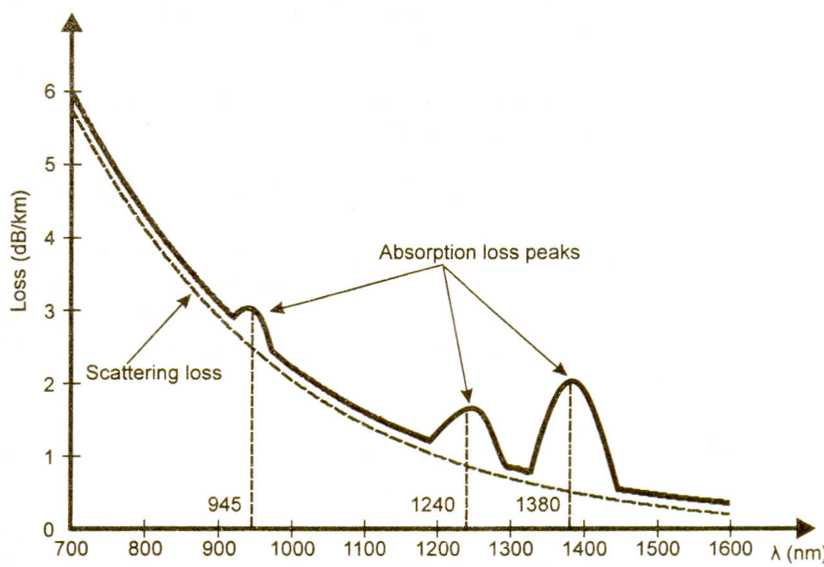


Figure 3.8 Typical spectral attenuation.

fabrication process and it is very hard to eliminate them. OH^- molecules have major peaks of absorption at 945, 1240, and 1380 nm. (See Figure 3.8.)

Transparent windows While this problem cannot be solved by eliminating the OH^- molecules, we can change the operating wavelength. Again look at Figure 3.8. There are three major regions, called transparent windows, where absorption is low. The first is located near 850 nm, the second near 1300 nm, and the third near 1550 nm. Typically, we can expect attenuation of about 4 dB/km near 850 nm, about 0.5 dB/km near 1300 nm, and about 0.3 dB/km near 1550 nm. The latter is the most widely used wavelength today in long-distance communications.

Observe that the main course of this graph is determined by scattering loss and its dependence on operating wavelength.

Detailed data sheets available from manufacturers might provide a graph of spectral attenuation similar to the one shown in Figure 3.8.

lculations Total tenuation

Fiber loss is the ratio of power at the output end of a fiber, P_{out}, to power launched into the fiber, P_{in}:

$$Loss = P_{out}/P_{in}, \tag{3.9}$$

where power is measured in watts.

In communications technology, we measure loss (attenuation) in decibels (dB):

$$Loss\,(\text{dB}) = -10\log_{10}(P_{out}/P_{in}), \tag{3.10}$$

where P_{out} and P_{in} are measured in watts. Since P_{out} is always less than P_{in} (this is why we use the term "attenuation," but not "amplification"), $\log_{10}(P_{out}/P_{in})$ *is always negative. To make the result of the calculations the positive number, the negative sign is used as Formula 3.10 shows.* This is accepted practice in fiber-optic communications technology.

Formulas 3.9 and 3.10 can be used to compute the total attenuation of an optical fiber. It is quite obvious that loss is proportional to fiber length, *L;* therefore, total attenuation characterizes not only the fiber losses themselves but also the fiber length, a fact that makes this characteristic very ambiguous. Indeed, if you know that for one specific fiber $Loss_1$ = 20 dB and for another fiber $Loss_2$ = 30 dB, could you possibly predict which fiber will have the lower loss characteristic? Of course not, because the first fiber could be 100 meters in length and the second 100 km long. This is why fiber-optic communications technology uses another characteristic: attenuation per unit of fiber length, *A*.

$$A\,(\text{dB/km}) = loss\,(\text{dB})/\mathit{fiber\ length}\,(\text{km}) \tag{3.11}$$

This quantity, A *(dB/km),* is called *attenuation* and it is one of the most important characteristics of an optical fiber. Attenuation is the number you will see on optical-fiber data sheets. This feature is sometimes called the cable-loss factor, *CLF,* or the attenuation coefficient, but most optical-fiber manufacturers use the term "attenuation."

Example 3.2.1

Problem:

A communications system uses an optical fiber whose attenuation, *A,* is 0.5 dB/km. Find the output light power if the input power is 1 mW and the link length is 15 km.

Solution:

We can attack the problem using Formulas 3.10 and 3.11:

$$
\begin{aligned}
-A\ (\text{dB/km}) &= (10\log_{10} P_{out}/P_{in})\ (\text{dB})/L(\text{km}) \\
\log_{10}(P_{out}/P_{in})\ (\text{dB}) &= [-A(\text{dB/km}) \times L(\text{km})]/10 \\
P_{out}/P_{in} &= 10^{-AL/10} \\
P_{out} &= P_{in} \times 10^{-AL/10},
\end{aligned}
\qquad (3.12)
$$

where P_{out} and P_{in} are given in watts.

For our example, $P_{out} = 1\ (\text{mW}) \times 10^{(-0.5 \times 15)/10} = 1\ (\text{mW}) \times 10^{-0.75} = 1\ (\text{mW}) \times 0.178 = 0.178$ mW.

Three important points can be drawn from Formula 3.12:

First, it is a key to understanding the connection between absolute attenuation and attenuation in dB. Indeed, suppose P_{in} is 1 mW and $AL = -3$ dB. Then $P_{out} = P_{in} \times 10^{-0.3} = 0.5$ mW, which means that absolute attenuation equals 0.5. If $AL = -10$ dB, then $P_{out} = P_{in}/10$, and so forth. On the other hand, if you know P_{in} and P_{out}, you can find the loss in dB. For example, if $P_{in} = 1$ mW and $P_{out} = 0.001$ mW, then $AL = -30$ dB, and so on.

Second, the negative sign in front of $AL/10$ is still further confirmation that attenuation means decreasing power, that is, that P_{out} is always less than P_{in}. The rule: *Loss = 10log P_{out}/P_{in} is always negative but attenuation in dB/km is always positive because of the negative sign in front of the logarithm.* For example, manufacturers display attenuation on their fiber data sheets as $A \leq 0.7$ dB/km at $\lambda = 1300$ nm.

Third, Formula 3.12 allows us to calculate the fiber-link length if given P_{in}, P_{out}, and A. The following formula can be easily derived from Formula 3.12:

$$L = (10/A)\ \log_{10}(P_{in}/P_{out}) \qquad (3.13)$$

Formula 3.13 allows us to calculate the maximum transmission distance imposed by attenuation, bearing in mind that the minimum value of P_{out} is determined by the sensitivity of the receiver.

Example 3.2.2

Problem:

Calculate the maximum transmission distance for a fiber link with an attenuation of 0.5 dB/km if the power launched in is 1 mW and the receiver sensitivity is 50 μW.

Solution:

Just plug the numbers into Formula 3.13:

$$L_{max}\ (\text{km}) = (10/A)\ \log_{10}\ (P_{in}/P_{out}) = (10/0.5)\ \log_{10}\ (20) = 26\ \text{km}$$

At first glance, this is not a very impressive distance, but fiber with such a level of attenuation is designed for short- and intermediate-distance applications.

In conclusion, remember that *total attenuation encompasses bending, scattering, and absorption losses* and bending losses are usually shown separately on the optical-fiber specification sheets.

Measuring Attenuation

There is a device called a power meter that allows us to measure the power of light. (For a detailed discussion of power meters, see Section 8.5.) The result is displayed in dBm, which is a specific unit of power in decibels when the reference power is 1 mW:

$$1\ \text{dBm} = -10\log(P_{out}/1\ \text{mW}) \tag{3.13a}$$

(Some power meters enable us to display the readings both in dBm and mW; others display readings in negative dBm.)

A diagram of an experimental arrangement for an attenuation measurement is shown in Figure 3.9. The procedure looks—and is—very simple: Connect a test fiber to the source and to the power meter and record the reading.

The key point here is this: Since *fiber connections to the source and to the power meter inevitably introduce additional losses,* your reading will reflect a sum of these losses and fiber attenuation. To exclude connection losses from your results, you need to take these measurements twice—with the fiber under the test and with a short piece of the same fiber serving as the reference point. You then subtract the second reading from the first. In this case, you can eliminate connection losses. The precision of this method is mainly determined by two factors: how accurately you can reproduce connection losses and how negligible is the attenuation introduced by a short piece of fiber.

This method is known as a cut method because it can be done by simply cutting a fiber under the test to get its short piece; this enables you to exclude the loss introduced by a light source connector.

To measure macrobending loss, simply wrap the fiber undergoing the test several times with a certain bend radius and observe the difference.

When measuring attenuation in a multimode fiber, special care should be taken to use a light beam filling the entire cross-sectional area of the core (called *overfilled launching*) to make sure that all possible modes are excited. (See the next section and Section 4.4.)

It is evident that with the arrangement shown in Figure 3.9, we can measure fiber loss. To calculate loss in dB when obtaining readings in dBm, use the following obvious formula:

$$\text{Loss (dB)} = P_{in}(\text{dBm}) - P_{out}(\text{dBm})$$

Be careful about signs; always remember that you want to present the fiber loss as a positive number. For example, if your readings are $P_{in} = -1.0$ dBm and $P_{out} = -1.5$ dBm, the fiber loss is 0.5 dB. To calculate attenuation based on your measurement, measure the fiber length and use Formula 3.11.

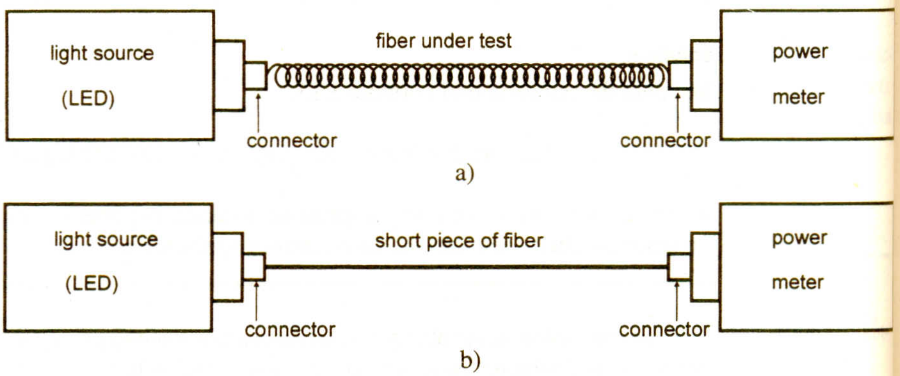


Figure 3.9 Experimental arrangement for measuring attenuation: (a) Measuring fiber attenuation with connection losses; (b) measuring connection losses.

3.3 INTERMODAL AND CHROMATIC DISPERSION

From its inception, fiber-optic communications technology promised the highest possible information-carrying capacity of any medium simply because its signal carrier—light—has the highest frequency among all the practical carriers. But as soon as the first fiber-optic communications systems appeared, it immediately became clear that the capacity of these systems was very far from theoretical expectations. The reason for this disappointment was modal, or intermodal, dispersion, which is the main subject of this section. We'll also consider another important phenomenon—chromatic dispersion.

Modes

What they are Numerical aperture, we have seen, is the number that characterizes the ability of a specific optical fiber to gather light. The larger the numerical aperture, the easier it is to direct light into an optical fiber (not simply to direct it, but to direct it in such a way as to save light inside the fiber). In other words, the greater the numerical aperture, the larger the amount of light that can be directed into and saved inside an optical fiber. It would seem, therefore, that we would want to have a numerical aperture as large as possible. From this point of view, plastic fiber, with an *NA* of 0.5192, looks better than silica fiber, whose *NA* is 0.2425, as calculated in Example 3.1.4. But this is not always true. There is a stumbling block that prevents us from making the numerical aperture larger. To understand this obstacle, we have to consider the modes in an optical fiber.

The fact is that light can propagate inside an optical fiber only as a set of separate beams, or rays. In other words, if we were able to look inside an optical fiber, we would see a set of beams traveling at distinct propagating angles, α, ranging from zero to the critical value, α_C. This picture is shown in Figure 3.10(a).

These different beams are called modes. We distinguish modes by their propagating angles and we use the word *order* to designate the specific mode. The rule is this: *The smaller the mode's propagating angle, the lower the order of the mode.* Thus, the mode traveling precisely along the fiber's central axis is the zero-order mode and the mode traveling at the critical propagation angle is the highest order mode *possible* for this fiber. (The zero-order mode is also called the fundamental mode.)

Many modes can exist within a fiber, and so a fiber having many modes is called a multimode fiber.

The number of modes How many modes an optical fiber can carry depends on the optical and geometric characteristics of a fiber. It's reasonable to expect that the larger the core diameter, the more light the core can accommodate and so there will be a greater number of modes. It is also reasonable to think that the shorter the wavelength of light, the more modes a fiber can accommodate. As for numerical aperture, the greater it is, the more light a fiber can gather and the more modes we would expect to see inside the fiber. We can therefore conclude that the number of modes inside a specific fiber should be proportional to the fiber diameter, *d,* and the numerical aperture, *NA,* and inversely proportional to the wavelength of the light used, λ.

The number of modes in an optical fiber is determined by the normalized frequency parameter, *V,* which is often called, simply, the *V* parameter. In fact, in your career you'll run across many terms for this parameter, such as *normalized cut-off frequency, characteristic waveguide parameter,* and others. We will just call it the "V number."

This number is equal to:

$$V = \frac{\pi d}{\lambda}\sqrt{(n_1)^2 - (n_2)^2}, \tag{3.14}$$

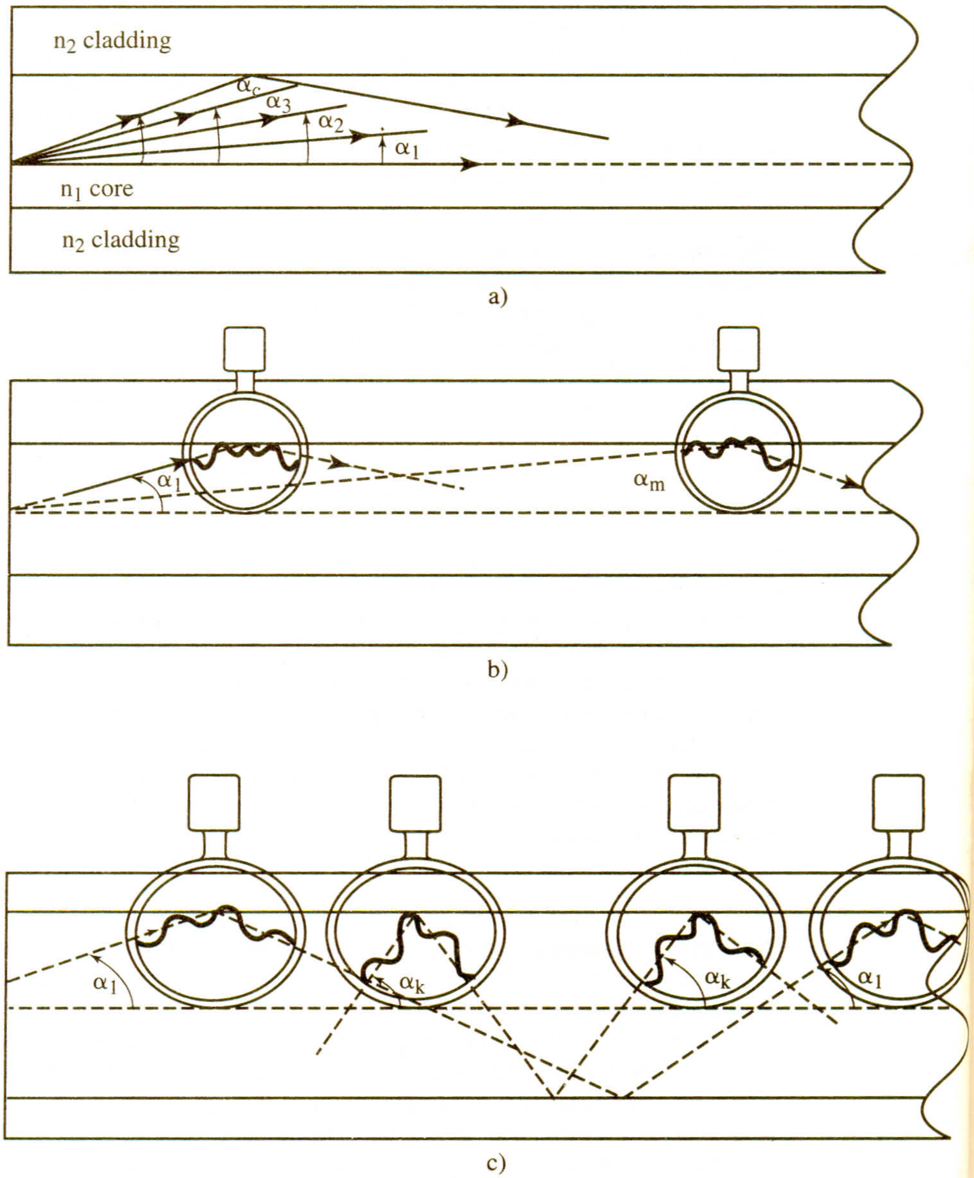


Figure 3.10 Modes in an optical fiber: (a) Modes as different beams; (b) different beams experience different phase shifts; (c) optical fiber supports only those modes (α_1) that complete the full zigzag at the same phase.

where d is the core diameter, λ is the operating wavelength, and n_1 and n_2 are refractive indexes of the core and cladding, respectively.

You may come across Formula 3.14 in different forms as, for example,

$$V = \frac{\pi d}{\lambda} NA, \tag{3.14a}$$

where NA is the numerical aperture. Another popular form of this same equation is:

$$V = \frac{\pi d n}{\lambda}\sqrt{2\Delta}, \tag{3.14b}$$

where $n = (n_1 + n_2)/2$ is the average refractive index and $\Delta = (n_1 - n_2)/n$ is the relative refractive index. All these forms follow from Formulas 3.5 and 3.8.

How can we calculate the number of modes? For a large V number (>20), the following formula for a step-index fiber can be applied:

$$N = V^2/2 \tag{3.15}$$

For a graded-index fiber (which is discussed on page 63) the formula is:

$$N = V^2/4 \tag{3.15a}$$

Formulas 3.14 and 3.15 confirm our discussion: The number of modes is directly dependent on the core diameter and the numerical aperture and inversely dependent on the wavelength.

Example 3.3.1

Problem:

Calculate the number of modes for a graded-index optical fiber if its core diameter $d = 62.5$, its numerical aperture $NA = 0.275$, and its operating wavelength $(\lambda) = 1300$ nm.

Solution:

Applying Formula 3.14a to calculate the V number, we get:

$$V = (\pi d NA)/\lambda = (3.14 \times 62.5 \times 10^{-6} \times 0.275)\ \mathrm{m}/1300 \times 10^{-9}\ \mathrm{m} = 41.5.$$

Applying Formula 3.15a to calculate the number of modes, we get:

$$N = (V)^2/4 = 431.$$

The actual number, N, we get from these calculations is 430.5625 but, obviously, the number of modes can only be an integer. That is why the calculation is given as 431.

The physics and importance of modes Why do we need to know about modes in an optical fiber? Because *the light beam emerging from a light source into the fiber breaks down into a set of modes inside the fiber. Within the fiber, total light power is carried by individual modes so that, at the fiber output, these small portions combine, producing an output beam with its power.*

One may wonder: Why does continuous light outside a fiber convert into discrete modes inside the fiber? The answer can be found in Figures 3.10(b) and 3.10(c), where "magnifiers" show the points of interest on a larger scale. There are three points we need to bring out here:

First of all, you will recall that light is made up of electromagnetic waves. The phases at which specific waves meet the core-cladding interface are different and depend on the distance the waves travel. But the distance inside a fiber is determined by the propagation angle. Thus, different waves traveling within the fiber at different propagation angles will strike the core-cladding interface at different phase angles, as Figure 3.10(b) shows for two waves.

A second critical point to understand is this: A wave experiences a phase shift when it is reflected; this shift depends on the propagation angle. This is shown in Figure 3.10(b), where the waves traveling at propagation angles α_1 and α_k have different phase shifts.

The third and most crucial point is that, after completing a full zigzag, wave α_1 strikes the core-cladding interface having the same phase as it had on the previous strike while wave α_k has a new phase. In other words, *wave α_1 reproduces itself after the whole cycle of propagation but wave α_k does not.* All these phase shifts depend on the propagation angles of specific waves traveling inside the fiber. Therefore, optical fiber supports only certain waves and the criterion for their selection is the propagation angle. For a detailed discussion of this intriguing topic see Section 4.4.

The concept of modes is a principal concern of ours because you will run across phenomena associated with it many times in the course of our discussions in this book. For now, however, this concept is of interest because it explains intermodal, often called modal, dispersion.

Modal (Intermodal) Dispersion

How input pulse is delivered within a fiber Let's consider a beam propagating inside a fiber, taking into account the mode concept. Don't forget that we are discussing fiber-optic *communications* technology; therefore, we are looking to use light to carry a communications signal. For the most popular form of digital transmission, *a light pulse represents logic 1, and no light pulse (darkness) represents logic 0. Such light pulses, radiated by a light source, enter a fiber, where each pulse breaks down into a set of small pulses carried by an individual mode. At the fiber output, individual pulses recombine and, since they are overlapping, the receiver sees one long light pulse whose rising edge is from the fundamental mode and whose falling edge is from the critical mode.* This explanation is depicted in Figure 3.11, where four modes are shown as an example.

Pulse widening caused by the mode structure of a light beam inside the fiber is called modal (intermodal) dispersion. This text uses the terms *intermodal* and *modal* interchangeably.

Calculations of pulse spread To ascertain why these individual light pulses arrive at the receiver end at different times, let's do some simple calculations. A zero-order mode traveling along the central axis needs time,

$$t_0 = L/v,$$

to reach the receiver end. Here, L is the link length and $v = c/n_1$ is the light velocity within the core having refractive index n_1, while c is the speed of light in a vacuum. The highest-order mode propagating at the critical angle—the critical mode—needs time,

$$t_C = L/(v\cos\alpha_C),$$

to complete its path. Reminding ourselves that $\cos\alpha_C = n_2/n_1$ (see Example 3.1.2), we can derive the formula for pulse widening stemming from intermodal dispersion:

$$\Delta t_{SI} = t_C - t_0 = \frac{Ln_1}{c}\left(\frac{n_1 - n_2}{n_2}\right), \tag{3.16}$$

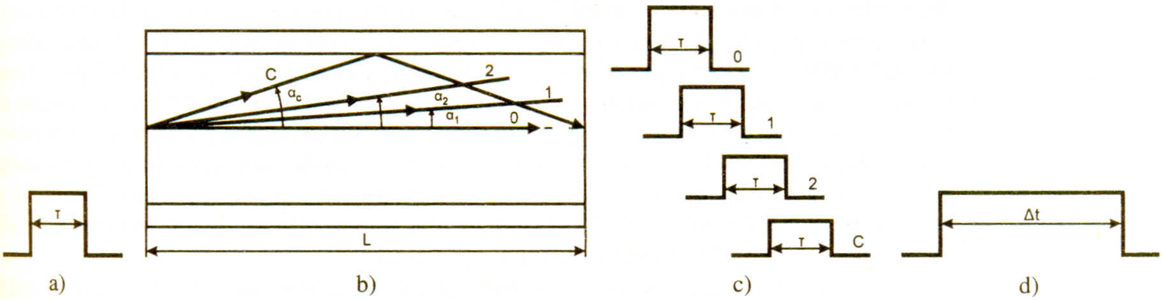


Figure 3.11 Intermodal (modal) dispersion: (a) Original pulse; (b) modes in an optical fiber; (c) pulses delivered by an individual mode; (d) resulting pulse.

where SI stands for step-index fiber. Using the relative refractive index $\Delta = (n_1 - n_2)/n$, Formula 3.16 can be rewritten as:

$$\Delta t_{SI} = t_C - t_0 = (Ln_1/c)\Delta, \tag{3.16a}$$

where approximation $n_2 \approx n$ has been used.

If the precision of your calculations allows you to neglect the difference between n_1 and n_2, you can derive this expression in still another form:

$$\Delta t_{SI} = t_c - t_0 = \frac{L}{2cn_2}(NA)^2, \tag{3.16b}$$

where NA is the numerical aperture. This version of the pulse-spreading formula is important because manufacturers provide you with a numerical aperture number, not with numbers n_1 and n_2.

Example 3.3.2

Problem:

How much will a light pulse spread after traveling along 5 km of a step-index fiber whose $NA = 0.275$ and $n_1 = 1.487$?

Solution:

From Formula 3.16b, replacing n_2 with n_1, we get

$$\Delta t_{SI} = (L \times NA^2)/(2\ cn_1) = (5 \times (0.275)^2)/(2 \times 3 \times 10^5 \times 1.487) = 423.8\,ns$$

Three things to make note of here:

(1) The fiber length is expressed in km and the speed of light in km/s.
(2) The unit used to measure pulse spreading is nanoseconds, ns (1 ns is equal to 10^{-9} s).
(3) We can assume $n_1 \sim n_2$ because their difference is about 0.02, which is much less compared with 1.5—their order of value.

Since pulse spreading is proportional to fiber length, it is sometimes useful to operate in terms of pulse spreading per unit length. If we do so using the above example, we get:

$$\Delta t_{SI}/L = 84.76\ \text{ns/km}$$

How intermodal dispersion restricts bit rate The importance of intermodal dispersion in pulse spreading cannot be overestimated. Let's see why. Suppose you need to transmit information at 10 Mbit/s (megabits per second). This means you want to transmit 10×10^6 pulses every second; in other words, the duration of each cycle is 100 ns. For simplicity's sake, assume that the duration of the input pulses is negligibly short. Nevertheless, these pulses will spread due to intermodal dispersion. For illustrative purposes, let's refer to the numbers discussed in Example 3.3.2, where we found that each pulse will spread up to 84.76 ns every kilometer. Therefore, the duration of each pulse will be 84.76 ns after the first kilometer transmission and 169.52 ns after the second. Figure 3.12 shows this situation.

As you can see, after the second kilometer pulses become so wide that they overlap and the light no longer carries any information. The same is true when you try to increase bit rate even for short-distance transmission. Consider the problem in Example 3.3.3.

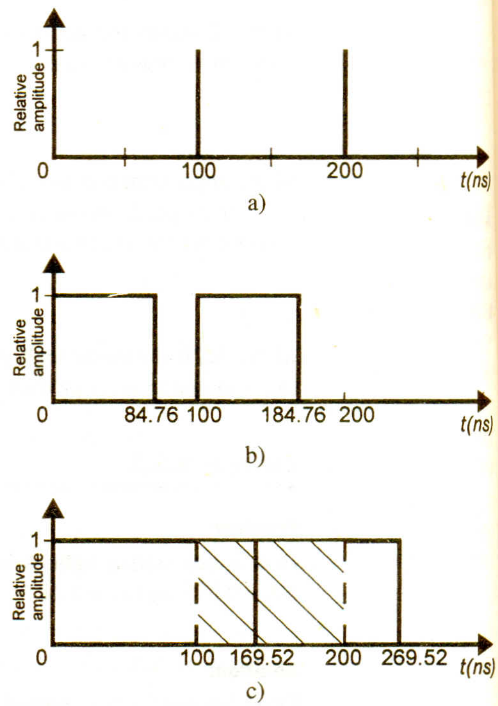


Figure 3.12 Pulse spreading after transmission: (a) Input pulses; (b) pulses after 1 km transmission in Example 3.3.2; (c) pulses after 2 km transmission in Example 3.3.2. Bit rate: 10 Mbit/s.

Example 3.3.3

Problem:

Find the maximum bit rate for the fiber discussed in Example 3.3.2 if the transmission length is 1 km.

Solution:

The solution is based on Formula 3.16a and Example 3.3.2. There are two key points to keep in mind as we work out this problem: First, we are able to distinguish pulses until they overlap. Secondly, let Δt be the width of an individual pulse. Then a 1-second interval can accommodate a certain number of these pulses before they will overlap. This number is equal to 1 second divided by

The First Solution to the Modal-Dispersion Problem—Graded-Index Fiber

Δt. If you divide this number by 1 second, you'll find the maximum bit rate. In other words *the maximum bit rate is equal to 1/*$\Delta t(s)$. We've computed in Example 3.3.2: $\Delta t_{SI} = 84.76$ ns; thus, the maximum bit rate is $1/(84.76 \times 10^{-9}$ ns$) = 11.8$ Mbit/s.

Obviously, we want to have a time gap between adjacent pulses to ensure their separation. If we take 25% of the cycle gap, we come up with a lower number for the maximum bit rate. In our example, a 25% gap results in the following: The maximum pulse width is $84.76 \times 1.25 = 105.95$ ns, which in turn gives $1/105.95$ ns $= 9.44$ Mbit/s (the maximum bit rate).

Draw a picture similar to the one in Figure 3.12. It will help you visualize the phenomenon of pulse spreading after transmission, which is the concept of intermodal dispersion.

Intermodal dispersion severely limits the bit rate of a fiber-optic link. Indeed, our examples show that the maximum bit rate might not be more than 12 Mbit/s. This is not a very impressive number. We certainly don't need fiber optics to transmit information at this bit rate; a coaxial cable can do that quite easily. In fact, this was the problem that telecommunications companies faced when fiber optics first became a serious contender as an information-carrying medium.

The First Solution to the Modal-Dispersion Problem—Graded-Index Fiber

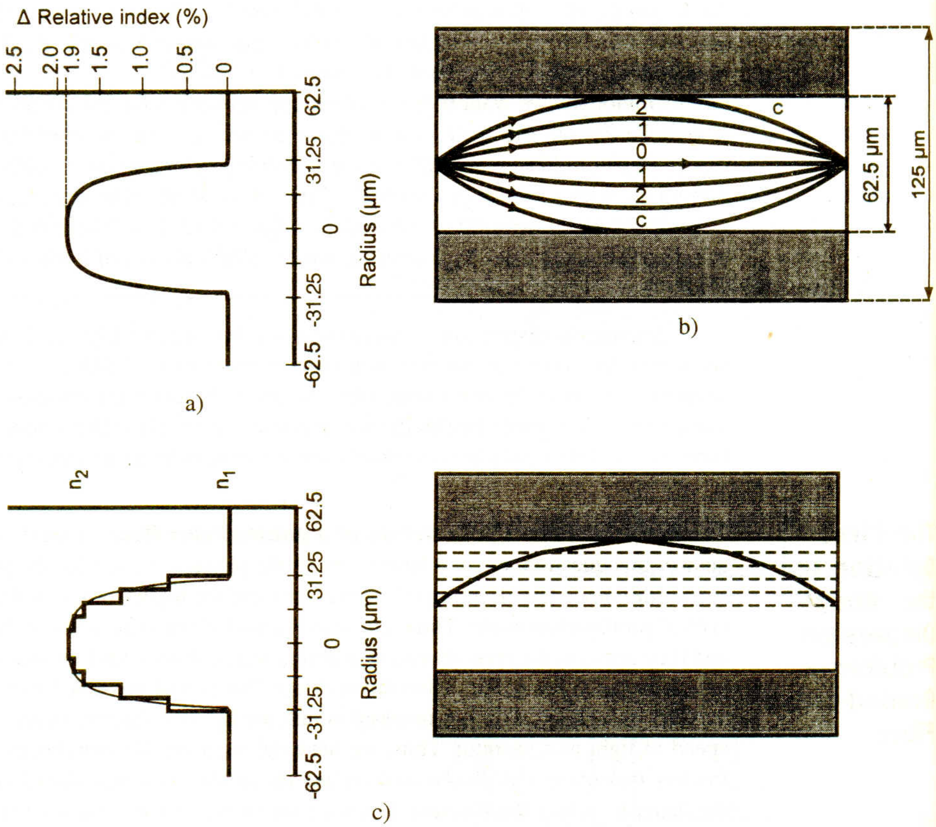
The basic idea and the structure of a graded-index fiber Can the problem be overcome? To answer this question, we first have to recall the physical reason for the problem. Within a core, the zero-order mode travels along the central axis and the higher-order modes travel at, or less than, the critical propagation angle. Thus, the beams travel at the same velocity but over different distances and they arrive at the receiver end at different times. If we could arrange it so that they would arrive simultaneously, we would solve the problem. But is that possible? In a word, yes. Recall that the velocity of light, v, within a material is defined by its refractive index, n: $v = c/n$, where c is the speed of light in a vacuum. Thus, we have the solution: *We can design the core with different refractive indexes so that the beam traveling the farthest distance does so at the highest velocity and the beam traveling the shortest distance propagates at the slowest velocity. Such fibers are called graded-index (GI) multimode fibers.* The principle of this action is clear from Figure 3.13.

Refer to the refractive-index profile in Figure 3.13(a). Observe how the refractive-index value varies gradually from n_1 at the core center to n_2 at the core-cladding boundary. This is why the fiber is called *graded index.* The higher-order modes move from the higher to the lower refractive indexes at each point along their path. This results in a change of direction in their propagation, shown as curve paths in Figure 3.13(b).

The core of a graded-index fiber can also be seen as a set of thin layers whose refractive indexes change slightly from one to another so that the layer at the central axis has refractive index n_1 and the layer at the cladding boundary has index n_2. This is how manufacturers physically make the fiber. The fabrication process consists of the deposition of molecular-thin layer after layer with a given refractive index, thus assembling the core and the cladding. A change in the refractive index is achieved by doping a certain number of atoms with material other than silica. (For more details on the fabrication process, see Chapter 7.)

One can understand the principle of light propagation in graded-index fiber by considering the behavior of light at the boundary of the two layers. Each individual interaction results in a small change of direction of the propagation. (The definition of the term *refractive index* also implies that it is a measure of how much a ray of light is bent when propagating from one medium into another.) This is illustrated in Figure 3.13(c). By making these layers smaller and smaller, we arrive at the gradually changed refractive index shown in Figure 3.13(a).

How well does a graded-index fiber reduce modal dispersion? You will recall that an input pulse is delivered within a fiber core in fractions and each of these fractions is carried by a different mode (Figure 3.11). The mode propagating along the centerline of a graded-index fiber—the



ure 3.13 Graded-ex (GI) multimode r: (a) Refractive-ex profile; (b) mode pagation; (c) princi- of action of graded-ex multimode fiber.

shortest distance—travels at the lowest speed because it meets the highest refractive index, as Figure 3.13(a) demonstrates. The mode traveling closer to the fiber cladding—the longer distance—propagates at the higher speed because it meets a lower refractive index. Hence, *the fractions of an input pulse delivered by the different modes arrive at the receiver end more or less simultaneously.* Therefore, intermodal dispersion will be reduced and the bit rate will be increased.

The formula for calculating pulse spreading (Δt) for graded-index fiber is given by [1]:

$$\Delta t_{GI} = \left(LN_1\Delta^2\right)/(8c), \tag{3.17}$$

where *GI* stands for the graded-index fiber, Δ is the relative index, c is the speed of light in a vacuum, and N_1 is the core group index of refraction. It follows from our definition of a graded-index fiber that its core refractive index is variable (see Figure 3.13). However, we can summarize the optical properties of the core as they are seen by the light propagating through a graded-index fiber by introducing one generalized number—N_1.

Example 3.3.4

Problem:

A graded-index fiber has $N_1 = 1.487$ and $\Delta = 1.71\%$. For a link 5 km in length, compute pulse spreading due to modal dispersion and determine the maximum bit rate.

Solution:

Formula 3.17 yields:

$$\Delta t_{GI} = (LN_1\Delta^2)/(8c) = (5 \text{ km} \times 1.487 \times (0.0171)^2)/(8 \times 3 \times 10^5 \text{km/s}) = 0.9 \text{ ns}.$$

Again, operating with pulse spreading per km length, one can compute:

$$\Delta t_{GI}/L = 0.18 \text{ ns/km}$$

Compare this answer with the numbers obtained in Example 3.3.2 for step-index fiber with similar parameters to see the much better dispersion characteristics of a graded-index fiber. Maximum bit rate is $1/\Delta t$. For the graded-index fiber of 1 km, one can get 5.5 Gbit/s, which is much better than the 11.8 Mbit/s obtained for a step-index fiber in Example 3.3.3. For a 5-km link, the maximum bit rate equals 1.1 G bit/s. Now you can see how the concept of reducing dispersion in a graded-index fiber works.

Two notes:

(1) Using Formula 3.8, it is easy to derive:

$$\Delta t_{GI} = (L\ NA^4)/(32\ c\ N_1^3), \tag{3.17a}$$

where approximation $n_1 \approx N_1$ was used.

(2) Compare Δt_{SI} (Formula 3.16a) and Δt_{GI} (Formula 3.17). You can see that $\Delta t_{GI} = \Delta t_{SI}(\Delta/8)$, again, assuming $n_1 \approx N_1$. Thus, a graded-index fiber has a modal dispersion $\Delta/8$ times less than that of a step-index fiber. You can verify this result using the numbers in Examples 3.3.2 and 3.3.4.

Graded-index fiber was the first solution to the modal-dispersion problem, but at a price: cost. This was because manufacturers had to expend more effort to control the complex index profile during the mass-production process. However, today this is no longer a problem and graded-index fiber is a popular transmission medium for short- and intermediate-distance networks.

A Better Solution to the Modal-Dispersion Problem—Singlemode Fiber

The structure of a singlemode fiber There is another, even better solution to the modal-dispersion problem. The underlying reason for the problem is the existence of many modes that deliver the same light pulse. So researchers asked themselves, "Why not limit the light beam inside the core to only one mode?" Doing so, they reasoned, would eliminate the problem completely. The result: advent of the singlemode fiber.

But just how was this accomplished? Refer again to Formulas 3.14, 3.15, and 3.16. They show that the number of modes is directly dependent on the core diameter, d, and the difference between refractive indexes n_1 and n_2. Hence, the simplest way to restrict the number of modes propagating inside the core to just one is to reduce the core diameter and relative refractive index. This approach is illustrated in Figure 3.14.

Pay attention to the core diameter, d, and the relative index, Δ, of a singlemode fiber; typically, d and Δ are as small as 8.3 μm and 0.37%, respectively. Compare these numbers with 62.5 μm and almost 2% of a graded-index fiber and you will see how one can make a fiber carry only one mode.

A word of caution: Don't try to insert $N = 1$, where N is the number of modes, into Formula 3.15 to obtain the critical V number. Remember, Formulas 3.14 and 3.15 work only for a large ($V > 20$) number of modes. A real singlemode condition is:

$$V \leq 2.405 \tag{3.18}$$

This condition was obtained from considerations that will be discussed in Chapter 6.

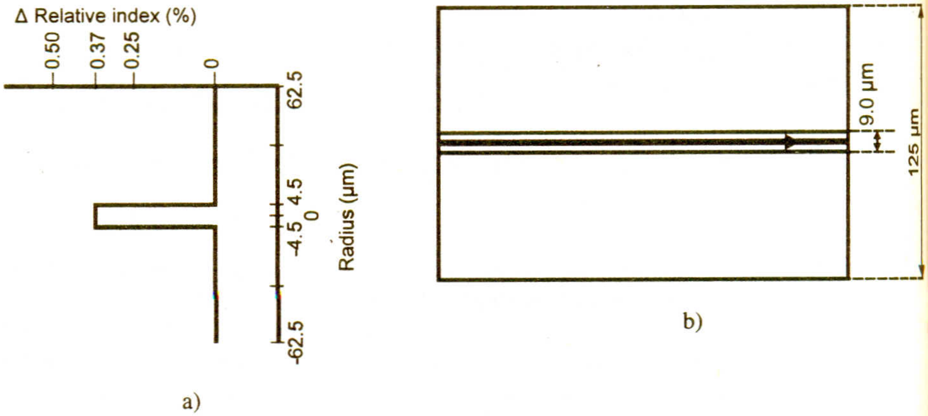


Figure 3.14 Step-index (SI) singlemode fiber: (a) Refractive-index profile; (b) mode propagation.

Review of the modal-dispersion problem To review the concept of dispersion for all three types of optical fiber, see Figure 3.15.

It is therefore clear that the singlemode fiber affords the best solution to the modal-dispersion problem. The drawback is that it is the most expensive fiber to manufacture and the most difficult to maintain, largely because of the difficulty in maintaining an accurate core size. Indeed, the core size of a singlemode fiber may vary from 4 to 11 μm. You can imagine how difficult it is to maintain this size with accuracy, yet avoid microbending and scattering problems during the mass-production process. What's more, a singlemode fiber is more prone to macro- and microbending losses and many other problems during installation and operation. However, the singlemode fiber is now the most popular type of link, particularly for long-distance communications, and it will surely penetrate other sectors of telecommunications. We will discuss this subject in more detail in Chapters 5 and 6.

Chromatic Dispersion

What it is Modal dispersion is not the only impediment to fiber bandwidth, or bit rate. Another type of dispersion, chromatic dispersion, also contributes to this drawback. The word *chromatic* is associated with colors, of course. You'll recall that the basic mechanism of dispersion involves different light beams carrying light pulses. The beams arrive at the receiver end at different times, causing the output light pulses to spread. In the case of modal dispersion, these different beams are different modes. But even within a single mode we might have the same problem if this mode were composed of light comprising different colors. Obviously, color is no more than an image and, in reality, we have to talk about wavelength.

Let's consider the zero-order mode, which travels precisely along the fiber's central axis. This beam is composed of light having several wavelengths simply because there is no source in nature that can radiate a single wavelength. And the key point to note here is that refractive index depends on wavelength; thus, $n = n(\lambda)$. In other words, for each specific wavelength, the refractive index is a specific—and different—number. You'll recall that the velocity of light, v, within a material is $v = c/n$, where c is the speed of light in a vacuum; therefore, *light of different wavelengths travels along the fiber at different velocities. Even if all of these beams propagate along the same path, they will arrive at the receiver end at different times. This results in the spreading of the output light pulse—chromatic dispersion.*

Chromatic dispersion plays the major role in limiting the bandwidth of a singlemode fiber, since modal dispersion is not a consideration here. (We will consider this in detail in Chapters 5 and 6.) This type of dispersion is important, too, for multimode fibers even though modal dispersion is the major factor limiting multimode-fiber bandwidth.

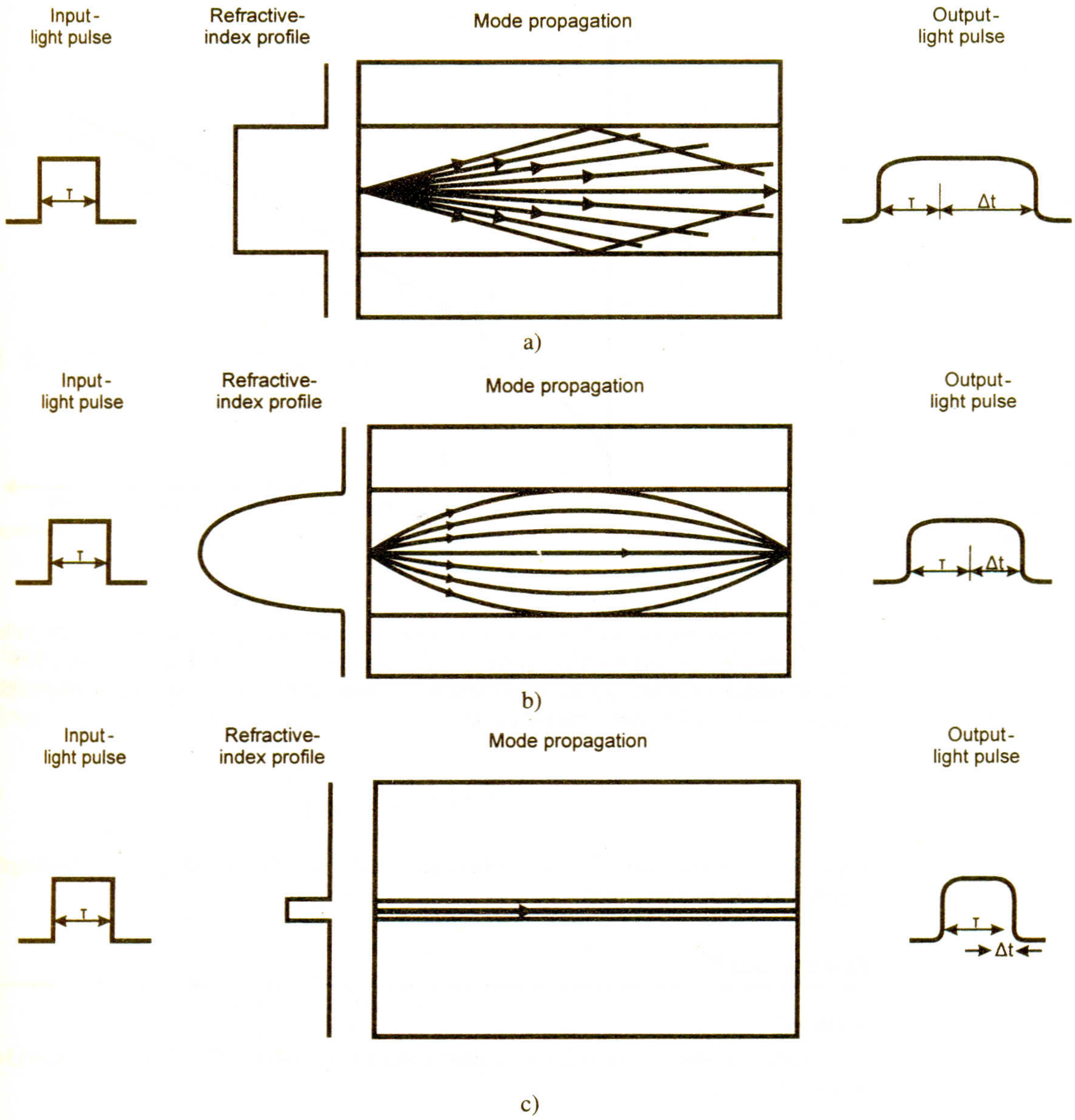


Figure 3.15 Dispersion in three types of optical fiber: (a) Step-index multimode fiber; (b) graded-index multimode fiber; (c) step-index singlemode fiber.

Calculating pulse spreading caused by chromatic dispersion Pulse spreading caused by chromatic dispersion can be calculated as follows:

$$\Delta t_{\text{chrom}} = D(\lambda) L \Delta\lambda, \tag{3.19}$$

where $D(\lambda)$ is the chromatic-dispersion parameter measured in picoseconds (ps) per nanometer (nm) and kilometer (km); thus, we have ps/nm · km; L is the fiber length in km and $\Delta\lambda$ is the spectral width of a light source in nm, the characteristic of how many wavelengths this source radiates.

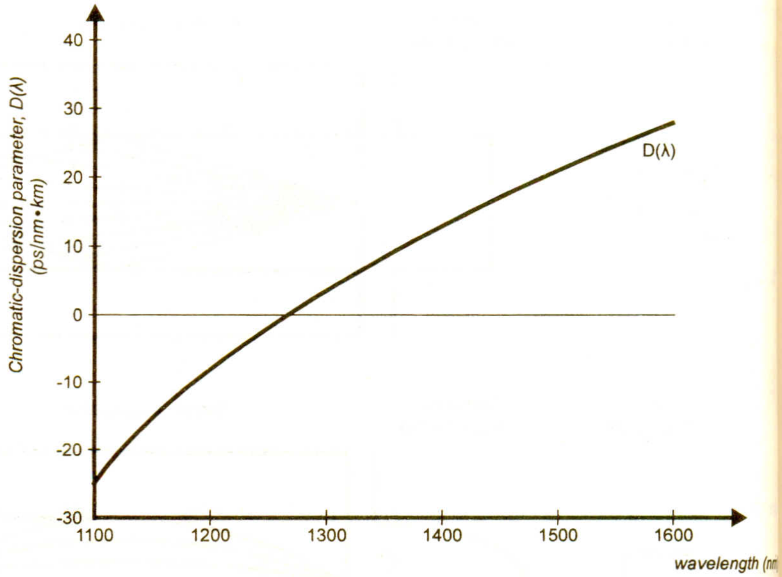


Figure 3.16 Chromatic-dispersion parameter.

The chromatic-dispersion parameter, $D(\lambda)$, is zero at the specific wavelength called the zero-dispersion wavelength. The graph of $D(\lambda)$ as a function of λ is shown in Figure 3.16.

Manufacturers specify the chromatic-dispersion parameter for multimode fibers either by giving its value or by giving the formula:

$$D(\lambda) = \frac{S_0}{4}\left[\lambda - \frac{\lambda_0^4}{\lambda^3}\right], \tag{3.20}$$

where S_0 is the zero-dispersion slope in ps/(nm^2 · km), λ_0 is the zero-dispersion wavelength, and λ is the operating wavelength.

Example 3.3.5

Problem:

What is the chromatic dispersion for a graded-index fiber if $S_0 = 0.097$ ps/(nm^2 · km), $\lambda_0 = 1343$ nm, and $\lambda = 1300$ nm?

Solution:

Inserting the numbers into Formula 3.20, one gets:

$$D(\lambda) = -4.38\,\text{ps}/(\text{nm}\cdot\text{km})$$

The minus sign comes from the formula and indicates that pulse spreading decreases as wavelength increases. For practical calculations, we can neglect this negative sign. This result tells us that the pulse spreading of this specific fiber is 4.38 ps (pico means 10^{-12}) per nm of wavelength radiated by a light source and per km of fiber length.

If we use an LED whose $\Delta\lambda = 50$ nm, we can calculate:

$$\Delta t_{\text{chrom}}/L = 219\,\text{ps/km} = 0.22\,\text{ns/km}$$

This number is the same order of value as the number 0.18 ns/km that we calculated for the modal dispersion of the same fiber. (See Example 3.3.4).

Total pulse spreading caused by modal and chromatic dispersion Total pulse spreading from both types of dispersion is calculated using the following formula:

$$\Delta t_{\text{total}} = \sqrt{\left(\Delta t^2_{\text{modal}} + \Delta t^2_{\text{chrom}}\right)} \tag{3.21}$$

where Δt_{modal} is the pulse spreading caused by modal dispersion and Δt_{chrom} is the pulse spreading that results from chromatic dispersion.

3.4 BIT RATE AND BANDWIDTH

Modal dispersion in optical fibers causes a significant restriction of bit rate. In response, two different types of optical fibers—graded-index multimode and singlemode—were developed to facilitate the problem. This is also true for chromatic dispersion. The result of these efforts is the variety of types and specifications of optical fibers that are available today designed specifically to satisfy a range of customer requirements. The major factor in these requirements is the information-carrying capacity of a link or network that can be characterized by bit rate or bandwidth. What these characteristics are and how we can calculate and use them are the topic of this section.

Bit Rate and Bandwidth Defined

Bit rate (some say "data rate") is the number of bits that can be transmitted per second over a channel. It is measured in bit/s. It is the direct measure of information-carrying capacity of a communications link or network for digital *transmission.* This is why it is also called the "information-transmission rate." *Bandwidth is the frequency range within which a signal can be transmitted without significant deterioration. It is measured in Hertz. It is the information-carrying capacity characteristic of a communications channel used for* analog *transmission.* These two characteristics, then, are obviously quite different. Bit rate—for digital transmission—and bandwidth—for analog transmission—are shown in Figure 3.17.

There is a difference between electrical bandwidth and optical bandwidth, which is discussed in Section 4.6.

What is the relationship between bit rate, *BR*, and bandwidth, *BW*? The simplest approach is to assume that the number of bits per second, bit/s, and the number of cycles per second, Hz, are the same; hence, $BW = BR$.

You often will find another relationship between bandwidth, *BW*, and bit rate, *BR*:

$$BW = BR/2 \tag{3.22}$$

This stems from the following consideration: Let's take the worst-case scenario, that is, when digital transmission is the sequence 1-0-1-0-1. . . . If we represent pulse waveform by sine waveform, we find that one period of sine covers two bits. This is shown in Figure 3.17(c). It is quite obvious that the bit rate is twice as high as the frequency, which results in Formula 3.22.

Which relationship—$BW = BR$ or $BW = BR/2$—we must use depends on the line codes. For instance, Figure 3.17c shows the non-return-to-zero (NRZ) format, which is the simplest line code. Here we use Formula 3.22. There are many other line codes for which the relationship between *BW* and *BR* is different. In general, *one can transmit several bits per second per hertz of a channel bandwidth (bit/s/Hz) by using various forms of modulations.* We will treat this topic in later chapters, but for the remainder of this discussion we will concern ourselves solely with $BW = BR$. Since fiber-optic communications technology uses the terms *bandwidth* and *bit rate* interchangeably, we will follow this pattern.

3

Optical Fibers—Basics

Optical fiber is the key to fiber-optic communications systems. The real deployment of these systems started only after commercially acceptable optical fibers appeared on the market. This is why we must pay close attention to all aspects of this component, the subject of this and the following chapter. This chapter is devoted to general issues in optical fibers, focusing on multimode fibers.

3.1 HOW OPTICAL FIBERS CONDUCT LIGHT

Imagine yourself a researcher working about thirty years ago. Your project: Find a way to transmit a light signal for communications. The concept of optical fibers—thin, transparent, flexible strands—is already known but any attempts to use them for communications have failed because the signal completely disappears after several feet of transmission. So herein lies our problem: We have to determine the conditions needed to transmit light through an optical fiber and resolve how these conditions can be effected in a practical manner.

Step-Index Fiber: The Basic Structure

Total internal reflection: refractive indexes of a core and cladding *An optical fiber is a thin, transparent, flexible strand that consists of a core surrounded by cladding.* Figure 3.1 shows this structure and the typical dimensions of optical-fiber components.

The core and the cladding of an optical fiber are made from the same material—a type of glass called silica—and they differ only in their refractive indexes. You recall that the refractive index is the number showing the optical property of a material, that is, how strongly the material resists the transmission of light. (See Table 2.1.) The definition of a refractive index, n, is given by Formula 2.2, rewritten here:

$$v = c/n, \quad (3.1)$$

where v is the velocity of light inside a material having a refractive index of n, and c is the speed of light in a vacuum. The core has the refractive index n_1, and the cladding has a different refractive index, n_2; thus, different optical properties make up the core and cladding of an optical fiber. If you look at the graph depicting how abruptly the refractive index changes across the fiber (Figure 3.1[a]), you will immediately understand why this structure is called a *step-index fiber.*

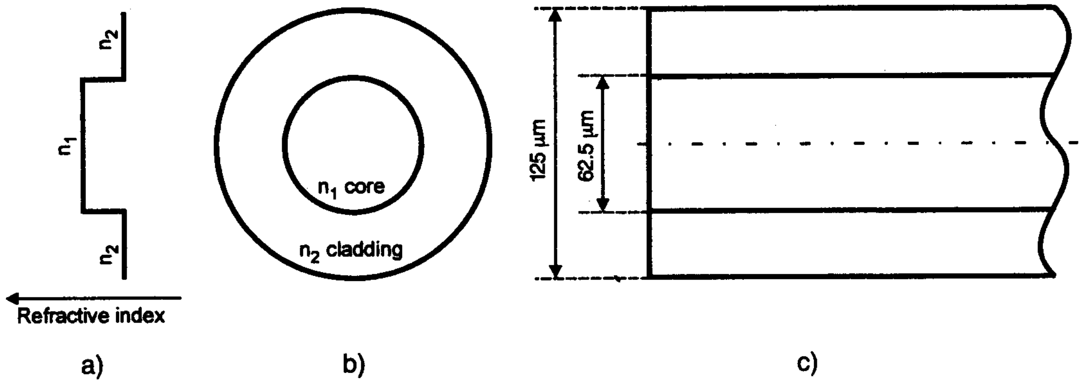


Figure 3.1 Basic structure of a step-index optical fiber: (a) Refractive-index profile; (b) cross section of an optical fiber—front view; (c) cross section of an optical fiber—right-side view.

The structure is made by applying a layer of cladding over the core. The difference in refractive indexes can be achieved by doping silica with different dopants. Because of the way a refractive index is changed, we can show the strict boundary—an optical boundary—between the core and cladding.

To complete this discussion of the basic makeup of optical fiber, it is necessary to stress that a third layer—a coating—is applied over the cladding to protect the entire structure. The coating is made of a different material from that of the core or cladding. The coating serves, then, as the first line of defense for a very fragile core-cladding structure. Without it, installers and users couldn't work with optical fibers.

To sum up, then, an optical fiber is always manufactured in three layers: core, cladding, and coating. This combination forms a bare fiber.

The question you want to have answered at this point is which layer—core or cladding—has the greater refractive index. The answer can be found in the basic understanding of what an optical fiber is designed for: to be a light conduit, that is, a flexible, transparent strand that transmits light with—*ideally*—no attenuation. Hence, as we saw in Chapter 2, we must make use of the concept of total internal reflection (see Figures 2.5, 2.6, and 2.7) to save light inside the core of an optical fiber. Therefore, *to achieve total internal reflection at the core-cladding boundary, the core's refractive index, n_1, must be greater than the cladding's index, n_2.* Under this condition, light can travel inside the core not only along its central pathway but also at various angles to this centerline, without leaving the core. Now we have created a light conduit. This conduit—an optical fiber—will save light inside the core even if it is bent. Figure 3.2 shows both situations (By the way, it is commonplace to hear those in the field say that "light bounces inside the core.")

Example 3.1.1

Problem:

a. The refractive index of a core is $n_1 = 1.48$ and the refractive index of a cladding is $n_2 = 1.46$. Under what condition will light be trapped inside the core?
b. Find this condition for a plastic optical fiber where $n_1 = 1.495$ and $n_2 = 1.402$.

Solution:

a. This condition is total internal reflection. To attain total internal reflection, we have to direct a light ray to the core-cladding boundary at the critical incident angle (see Figure 2.5). What

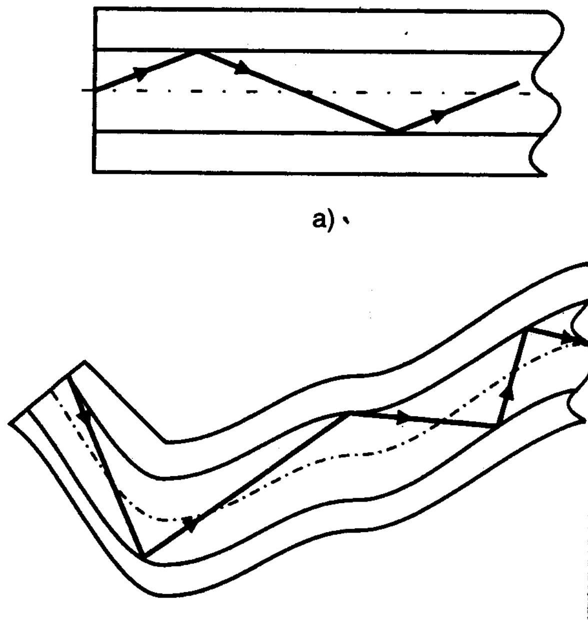


Figure 3.2 Light propagation inside an optical fiber: (a) Straight fiber; (b) bent fiber.

is this angle? We find it by using Snell's law (Formula 2.3): $n_1 \sin \Theta_1 = n_2 \sin \Theta_2$. The criti angle is reached when $\Theta_2 = 90°$ (again, see Figure 2.5); hence, $n_1 \sin \Theta_{1C} = n_2$ and

$$\sin \Theta_{1C} = n_2/n_1$$

Therefore, $\Theta_{1C} = \sin^{-1}(n_2/n_1) = \sin^{-1}(0.9865) = 80.57°$.

b. Besides silica (glass) optical fiber—the most popular type in today's deployed systems an optical fiber made from plastic also exists. Let us repeat the same type of calculation plastic optical fiber where $n_1 = 1.495$ and $n_2 = 1.402$:

$$\Theta_{1C} = \sin^{-1}(1.402/1.495) = \sin^{-1}(0.9378) = 69.68°$$

Observe the difference between the two critical incident angles: Where does this differe come from?

The above example also helps us remember this important fact: n_{core} (n_1) is always grea than $n_{cladding}$ (n_2). Indeed, we found that $\sin \Theta_{1C} = n_2/n_1$; thus, n_1 cannot be less than n_2 as property of sine function dictates.

Total internal reflection: critical incident angle and critical propagation angle It is i portant to point out at this juncture that two key terms often confuse newcomers to this field: *cri ical incident angle* and *critical propagation angle*. You must distinguish between them. *The cri cal propagation angle, α_C, is the angle the beam makes with the centerline of the optical fiber. is very often referred to, in fiber optics parlance, as the "critical angle.") The critical incid angle, Θ_{1C}, is the angle the beam makes with the line perpendicular to the optical boundary b tween the core and the cladding* (again, see Figure 2.5). Both angles are shown in Figure 3.3.

It is clear from right triangle A-B-C, Figure 3.3, that $\alpha_C = 90° - \Theta_{1C}$. In Example 3.1.1a found that $\Theta_{1C} = 80.57°$; hence, $\alpha_C = 9.43°$.

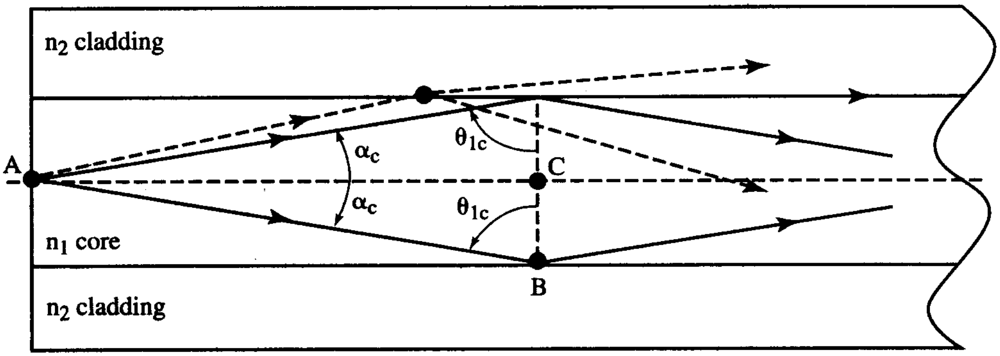


Figure 3.3 Critical incident angle, Θ_{1C}, and critical propagation angle, α_C.

Why is the critical propagation angle, α_C, so important? Suppose a beam travels within this optical fiber at $\alpha = 10° > \alpha_C$. Hence, $\Theta_1 = 80° < \Theta_{1C}$, which means that the condition of total internal reflection has been violated. Therefore, the incident beam will divide in two: a reflected beam, which will be saved, and a refracted beam, which will be lost. This beam, which is at $\alpha > \alpha_C$ with the center axis, is shown in Figure 3.3 as a dotted line. (Refer again to Figure 2.4.) Keep in mind that *a beam strikes the core-cladding interface millions and millions of times while traveling through the fiber; therefore, if even a microscopic portion of the beam is lost every time it hits this boundary because of refraction, the beam will be completely lost after traveling only a short distance.* This is what is meant when we speak of unacceptably high attenuation. Thus, *total internal reflection is the condition necessary for using optical fiber for the purpose of communication.* The critical propagation angle, α_C, represents the requirement to achieve this condition. In conclusion, then, *to save light inside an optical fiber, it is necessary to direct rays at this critical propagation angle—or even at a lesser angle.*

From here on, we can forget about the critical incident angle, Θ_{1C}, since it does not apply to fiber-optic technology. We are only interested in knowing the critical propagation angle, α_C, since this angle dictates how we must direct the light inside the optical fiber. We must never lose sight of the crucial role this angle plays. It is a supplement to the critical incident angle, Θ_{1C}, and therefore represents the condition necessary for achieving total internal reflection.

Example 3.1.2

Problem:

a. The refractive indexes of the core and the cladding of a silica fiber are 1.48 and 1.46, respectively. What is the critical propagation angle?
b. Find this angle for a plastic optical fiber ($n_1 = 1.495$ and $n_2 = 1.402$).

Solution:

a. First, let's derive the formula. In Example 3.1.1a we found that $\sin\Theta_{1C} = n_2/n_1$. Since $\alpha_C = 90° - \Theta_{1C}$, $\sin\Theta_{1C} = \cos\alpha_C$; hence, $\cos\alpha_C = n_2/n_1$. Thus, one can derive: $\sin\alpha_C = \sqrt{(1-\cos^2\alpha_C)} = \sqrt{(1-(n_2/n_1)^2)}$. Hence,

$$\alpha_C = \sin^{-1}\sqrt{(1-(n_2/n_1)^2)}$$

Now let's plug in the numbers:

$$\alpha_C = \sin^{-1}\sqrt{(1-(1.46/1.48)^2)} = 9.43°$$

This result is clear from Example 3.1.1a, since $\alpha_C = 90° - \Theta_{1C}$.

b. Now calculate the critical propagation angle for a plastic optical fiber:

$$\alpha_C = \sin^{-1}\sqrt{\left(1-(1.402/1.495)^2\right)} = 20.32°$$

At this point, it is imperative to bring into our discussion a very important formula: *The critical angle of propagation, α_C, is determined by only two refractive indexes, n_1 (n_{core}) and n_2 ($n_{cladding}$):*

$$\alpha_C = \sin^{-1}\sqrt{1-\left(\frac{n_2}{n_1}\right)^2} \qquad (3.2)$$

It is important to underscore the logic that led us to this formula: *To save light inside a strand of fiber, we need to have it strike the core-cladding boundary at the critical incident angle Θ_{IC}, or above it, in order to provide total reflection of this light; to make light fall at or above that angle, we have to direct it so that it is at or below the critical propagation angle, α_C, with respect to the centerline of the fiber, as we've already seen.*

Launching the Light: Understanding Numerical Aperture

Acceptance angle The next question that arises is, how can we direct this beam so that it does indeed fall at or below the critical propagation angle? The light, of course, must come from some source, such as an LED or an LD. This source is outside the fiber; therefore, we have to direct it into the fiber. Figure 3.4 shows how light radiated by a light source is coupled to an optical fiber.

At the gap-fiber interface, the beam at angle Θ_a is the incident beam and the beam at angle α_C is the launched one, which is the refracted beam with respect to gap-core interface (the reflected beam is not shown here). It will help you to understand this explanation if you look at Figure 3.4. The formal relationship between Θ_a and α_C can be derived using Snell's law. From Figure 3.4 one can find:

$$n_a \sin\Theta_a = n_1 \sin\alpha_C \qquad (3.3)$$

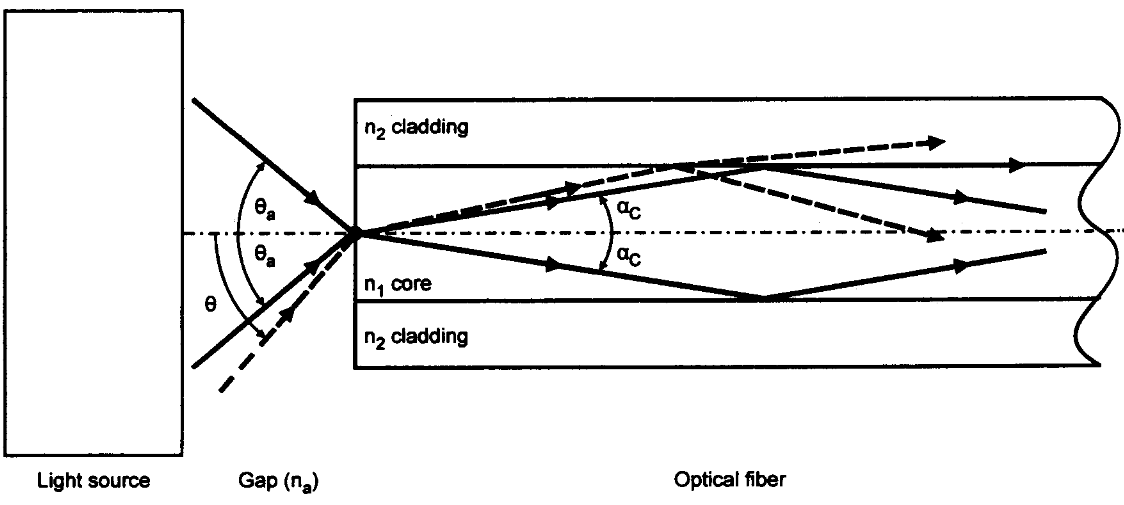


Figure 3.4 Launching light into an optical fiber.

If the gap between a light source and a fiber is air, then n_a is very close to 1 ($n_a = 1.0003$). Therefore,

$$\sin\Theta_a = n_1 \sin\alpha_C \tag{3.3a}$$

Formula 3.3, in a sense, states the following principle: *To save light inside a fiber (to provide total internal reflection, that is) all rays must propagate at critical angle α_C or less. In order for us to maintain the light inside the fiber at this angle, we have to direct it from outside the fiber (from the light source, remember) at angle Θ_a or less.*

It's clear from Figure 3.4 that angle Θ_a is a spatial angle. Light will be saved inside the fiber if it comes from a light source bounded by the cone $2\Theta_a$. This is why we call *angle $2\Theta_a$ an acceptance angle.* (Sometimes you might meet an acceptance angle defined simply as Θ_a, without the coefficient 2.)

The dotted line in Figure 3.4 indicates a ray that comes in at an angle exceeding the acceptance angle, Θ_a, outside the fiber. It is obvious the ray will travel inside the fiber at an angle exceeding the critical propagation angle, α_C. This will result in the partial refraction of the ray. In other words, if a ray is not within the acceptance cone defined by $2\Theta_a$, it will be lost while traveling inside the fiber. Simply put, *exceeding acceptance angle $2\Theta_a$ is just beyond the requirement for having total internal reflection inside a fiber.*

Example 3.1.3

Problem:

a. What is the acceptance angle for the fiber when $n_1 = 1.48$ and $n_2 = 1.46$?
b. What is the acceptance angle for the plastic optical fiber?

Solution:

a. From Snell's law, $n_a \sin\Theta_a = n_1 \sin\alpha_C$. For air, $n_a = 1.00$. From Example 3.1.2, the critical propagation angle $\alpha_C = 9.43°$; hence, $\sin\Theta_a = 1.48 \sin 9.43° = 0.2425$. One half of acceptance angle $\Theta_a = \sin^{-1} 0.2425 = 14.033°$. Therefore, the acceptance angle is $2\Theta_a = 28.07°$.
b. $\Theta_a = \sin^{-1}(1.495 \sin 20.32°) = \sin -1(0.5192) = 31.27°$
   Thus, the acceptance angle is $2\Theta_a = 62.54°$.

Observe the difference in values of the acceptance angles for these two fibers.

All these considerations serve only to better explain how we can save light inside an optical fiber. Physically, we have two components of a system that have to be connected: an optical fiber and a light source (LED or LD). We don't see any angles—either a critical propagation angle or an acceptance angle—and the only thing that we can do is direct light from the source into the fiber. This is why fiber-optic communications technology does not operate with any angles but, instead, integrates all these factors into one characteristic: numerical aperture (NA).

Numerical aperture Numerical aperture, NA, is:

$$NA = \sin\Theta_a \tag{3.4}$$

This definition underscores the meaning of the numerical aperture. To compute the numbers, however, it's better to use another form of this expression, which can be derived as follows:

$$NA = \sin \Theta_a$$

$$\sin \Theta_a = n_1 \sin \alpha_C \text{ and } \sin \alpha_C = \sqrt{\left(1 - (n_2/n_1)^2\right)} \text{ (see Formula 3.2); hence,}$$

$$NA = n_1 \sin \alpha_C = n_1 \sqrt{\left(1 - (n_2/n_1)^2\right)} = \sqrt{(n_1)^2 - (n_2)^2}$$

This is the formula most often used:

$$NA = \sqrt{(n_1)^2 - (n_2)^2} \qquad (3.5$$

Example 3.1.4

Problem:

a. What is the numerical aperture of silica fiber with $n_1 = 1.48$ and $n_2 = 1.46$?
b. What is the numerical aperture of plastic fiber where $n_1 = 1.495$ and $n_2 = 1.402$?

Solution:

a. If we plug the numbers into Formula 3.5, we get: $NA = \sqrt{(1.48)^2 - (1.46)^2} = 0.2425$. W can verify our result by using Formula 3.4: $NA = \sin \Theta_a$. We have found in Example 3.1 that $\sin \Theta_a = n_1 \sin \alpha_C = 0.2425$; hence, $NA = 0.2425$.
b. $NA = \sqrt{(1.495)^2 - (1.402)^2} = 0.5192$.
Verify the answer: $NA = \sin 31.27° = 0.5192$.

Observe the difference in the values of *NA* for these two fibers.

Have you noticed that all the formulas we've used in this chapter depend on only two vari ables—n_1 and n_2? This is so because the formulas are mathematical forms of the same basic ide total internal reflection for light traveling inside an optical fiber.

We can best summarize our discussion by this simple flow diagram: $\Theta_{1C} \rightarrow \alpha_C \rightarrow$ $\rightarrow NA$. What it shows is that *fiber-optic communications technology makes use of numeric aperture,* NA, *which describes the ability of an optical fiber to gather light from a source a then the ability to preserve, or save, this light inside the fiber because of total internal reflectio*

The formula expressing this statement thus becomes:

$$NA = \sin \Theta_a = \sqrt{(n_1)^2 - (n_2)^2} \qquad (3.4) \text{ and } (3.$$

From here on, all we need to know is the numerical aperture, *NA, which is the only numb that you will find in the optical-fiber data sheets.* It is essential that you remember the meaning this number. It represents the condition of total internal reflection inside the optical fiber, a co dition that is absolutely necessary if we want to use optical fiber for communications.

Would we ever want to change the *NA*? Remember, *NA* characterizes the fiber's ability gather light from a source. Thus, the answer is yes, because for different applications it might necessary to use fibers with different *NAs*. It would seem that if we wanted to change the N (Formula 3.5), we would have to change either n_1 (the core refractive index) or n_2 (the claddi refractive index). But let's take a closer look at Formula 3.5.

Fiber-optic communications technology operates not with the refractive indexes of t core and the cladding themselves but with their difference, Δn. The above discussion made clear, we trust, why the difference, Δn, not the values of n_1 and n_2, is important. We define the difference, Δn, as:

$$\Delta n = n_1 - n_2 \tag{3.6}$$

Note that this value is always positive. It is very common to use the *relative difference of the refractive indexes,* Δ, often called the *relative index,* which is defined as follows:

$$\Delta = (n_1 - n_2)/n, \tag{3.7}$$

where n, the average refractive index, equals $(n_1 + n_2)/2$. You can find a formula similar to (3.7) with n_1 or n_2 in the denominator. The numbers you will calculate with these variations change very slightly because, in reality, n_1 is very close to n_2.

Using this quantity, we can introduce another formula for numerical aperture, NA. This is the simple derivation: $NA = \sqrt{(n_1)^2 - (n_2)^2} = \sqrt{((n_1 - n_2)(n_1 + n_2))} = \sqrt{(\Delta n)(2n)} = \sqrt{((\Delta n/n)(2n)^2)}$. Thus, we arrive at this formula:

$$NA = n\sqrt{(2\Delta)} \tag{3.8}$$

This formula underscores the following: n_1 and n_2 are not important in themselves but only in their average and relative difference. Thus, to change NA, we need to vary n and Δn; this is what manufacturers really do. By varying these two parameters, manufacturers are able to change NA over a relatively wide range (from 0.1 to 0.3 for a silica fiber).

Can we measure NA? Not directly. We have to first measure the power of light immediately after it is radiated by an LED. Then we make a second measurement by placing a short piece of fiber between an LED and a power meter. The first measurement gives us the power P_o, the second measurement, the power P_{in}. Now the numerical aperture can be estimated by the simple formula $NA = \sqrt{P_{in}/P_0}$. (See Section 9.1.)

3.2 ATTENUATION

Assume that you measure light power before it is directed into an optical fiber and then measure it again as it emerges from the fiber. Would you expect to get the same numbers? Of course not. This is because we understand intuitively that the power coming out of the fiber should be less than the power entering it. But apart from an "intuitive" understanding, we want to have a scientific explanation for this phenomenon. And it is simply this: Every transmission line introduces some loss of signal power. This is the phenomenon of "attenuation." In fiber-optic communications technology, *attenuation is the decrease in light power during light propagation along an optical fiber.*

From this definition, light loss caused by violation of the condition of total internal reflection when launching light into a fiber (see Figures 3.3 and 3.4) is supposed to be included in the total attenuation within the fiber. But, practically speaking, fiber-optic communications technology never considers this loss as a component of total attenuation because, without total internal reflection, optical fiber simply doesn't work as a communications conduit. As emphasized several times in Section 3.1, total internal reflection is an absolutely necessary condition for using optical fiber in communications systems. As an analogy, consider the situation where people ask you about your health. Nobody ever asks whether or not you can breathe, do they? Yet breathing is a necessary condition for living. Therefore, the point to keep clearly in mind as you read what follows is this: *When light is coupled to an optical fiber for the purpose of communication, at-tenuation in the optical fiber means a power loss for reasons other than failure to achieve total internal reflection initially.* The following discussion explores these other reasons.

Bending Losses

Macrobending loss One of the most important advantages of today's optical fiber is its flexi-bility. Just imagine for a moment that you are holding a glass rod that conducts light perfectly but is rigid. Can you use that rod for communications? Certainly not because you'd have to install it in different environments; therefore, you would have to be able to bend it. That is why real opti-cal communications was born with the advent of optical fibers which allow installers to bend cable as necessary. How much this flexible strand can be bent is our next consideration.

Figure 3.5 shows two conflicting situations: (1) The beam forms a critical propagation angle with the fiber's central axis at the straightened, or flat, part of the fiber. (2) But the same beam forms a propagation angle that is more than critical when it strikes the boundary of the bent fiber. The result is failure to achieve total internal reflection in the bent fiber, which means that some portion of the beam is escaping from the core of the fiber. Hence, the power of the light ar-riving at its destination will be less than the power of the light emitted into the fiber from a light source. In other words, *bending an optical fiber introduces a loss in light power, or attenuation.* This is one of the major causes of the total attenuation that light experiences while propagating through an optical fiber.

At this point you're no doubt wondering how the problem can be overcome. Manufacturers of optical fiber have learned how to reduce a fiber's bending sensitivity by designing refractive-index profiles. Unfortunately, improvement in bending sensitivity can be achieved only at the ex-pense of the degradation of a fiber's other parameters. This is why manufacturers inform users what bending loss can be induced at a certain bending radius. For example, one turn at a 32-mm diameter mandrel causes a 0.5-dB (approximately 11%) bending loss for one popular type of fiber. Sometimes manufacturers include the minimal bending radius in their data sheets.

Thus, we can say that there is no straightforward method to eliminate this cause of attenu-ation. The only thing we can do about it is to be cautious when bending an optical fiber.

Bending can change not only the optical properties but also the mechanical characteristics of optical fibers. To prevent this, installers and users have to take precautions in bending fibers. The rules of thumb regarding minimum bending radius are these: A bending radius should be more than 150 times the cladding diameter of the fiber for long-term applications and more than

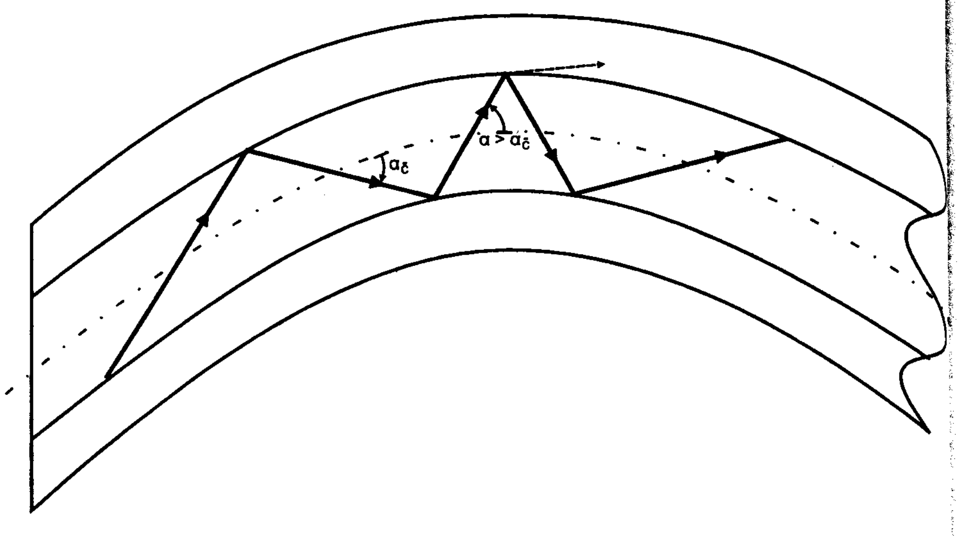


Figure 3.5 Bending loss.

How to Make Bending Loss Work for Us

Paradoxically, bending loss has a positive side. Sometimes we need to introduce well-controlled attenuation in a fiber-optic communications link. Specific passive components, called attenuators, actually do this job for us. One type of attenuator is based on the phenomenon of bending loss. Its advantage is that you need only make several turns of the fiber that you are using for transmission, so you don't need to introduce external components to the fiber component. (As we will see, introducing external components always presents problems.) With this type of attenuator, you can easily control attenuation quantitatively by controlling the number of turns the fiber makes around a given bending radius.

Another positive application is to use bent fiber as a mode filter—a device that reduces the number of modes in a fiber. (Modes are taken up in the following section.)

A fusion splicer (see Chapter 8) uses bending losses to control splicing quality. An example of one more positive use of the bending effect is through a device called the *fiber identifier.* This measuring instrument bends an optical fiber slightly and uses escaping light to control the data traffic within the fiber. (See Chapter 8.)

100 times the cladding diameter for short-term applications. Since the cladding diameter for silica fiber is usually 125 μm, we get the numbers 19 mm and 13 mm, respectively. But remember, bending fiber under these radii will damage it.

Microbending loss The type of loss we discussed above is called *macrobending* loss, since it is caused by bending the entire optical fiber. Another type of loss—*microbending* loss—is also caused by failure to achieve the condition of total internal reflection Figure 3.6 shows what this type of loss looks like in an optical fiber.

Some imperfections in the geometry of the core-cladding interface might result in microconvexity, or microdent, in that area. Although light travels along the straight segment of a fiber, the beam meets these imperfections and changes its direction. The beam, which initially travels at the critical propagation angle, after being reflected at these imperfection points, will change the angle of propagation. The result is that the condition of total internal reflection is not attained and portions of the beam will be refracted; that is, they will *leak* out of the core. This is the mechanism of microbending loss.

Now we can give formal definitions to these types of loss: *Macrobending is loss caused by the curvature of the entire fiber axis. Microbending is loss caused by microdeformations of the fiber axis.* To find the connection between the given definitions and the above explanations, we need to realize that the fiber's centerline, or axis, is the imaginary line. *In reality, this line is determined by the core-cladding geometry.* This is why microdeformations of the fiber axis are microdeformations of the core-cladding boundary, as Figure 3.6 shows.

Fiber-optic users can do nothing to overcome microbending loss except ask manufacturers to improve the quality of their optical fibers. Fortunately, the fiber-manufacturing process is so

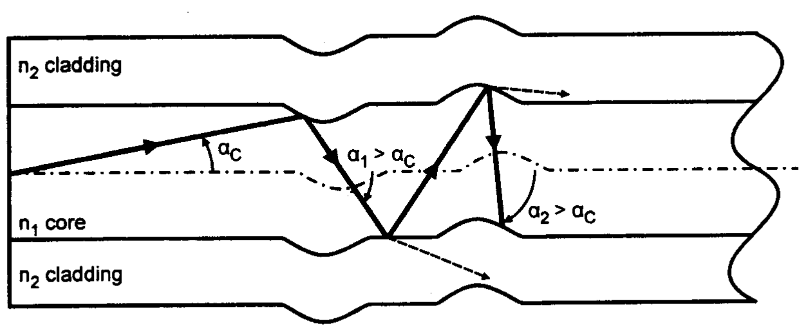


Figure 3.6 Microbending loss.