Course: TCET 4102 Fiber-optic communications

Module 2: Optical fiber

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Module 2: Light propagation in optical fiber

1. Review of Module 1.
2. Light propagation in an optical fiber:
   - Attenuation: absorption, scattering, and bending losses.
   - Spectral attenuation.
   - Self study: Launching light into optical fiber ➔ numerical aperture.


Notes:
- The figure numbers in these modules are the same as in the textbook. New figures are not numbered.
- Always see examples in the textbook.

Key words
- Fiber core
- Fiber cladding
- Total internal reflection
- Loss of optical power
- Light scattering
- Bending loss
- Light absorption
- Attenuation
- Spectral attenuation
- Numerical aperture
Introduction:
Block diagram of a fiber-optic communications system

Figure 1.1  Block diagram of a fiber-optic communications system.

Note: The figure numbers in these modules are the same as in the textbook. New figures are not numbered.
• Basic block diagram of a fiber-optic communications system
A fiber-optic communications system is a particular type of telecommunications system. Information to be conveyed enters a transmitter (Tx), where its electronics process it, that is, prepares the information signal for transmission. The transmitter also converts the signal into optical form and the resulting light signal is transmitted over optical fiber. At the receiver end, an optical detector converts the light back into an electrical signal, which is processed by the receiver’s electronics to extract the information and present it in a usable form (audio, video, or data output).

• Telecommunications industry has turned to optical technology for the following reason: Transmission capacity (bandwidth) of a link is proportional to the frequency of a carrier, $f_C$ (that is, $C \text{ (bit/s)} \sim f_C \text{ (Hz)}$). Since light has the highest $f_C$ (hundreds of THz) among practical signal carriers, then optical communications systems—that use light as a signal carrier—can achieve the highest transmission capacity.
Introduction:
Block diagram of a fiber-optic communications system.

Detailed block diagram of a fiber-optic communications system.
Source: Atlas of cyberspace.
• The trend today is to produce more and more information at a faster and faster rate. Telecommunications, which is responsible for delivering information from one point to another, plays an increasingly important role in modern society.

• Optical communications is the linchpin of the telecommunications industry; Optical networks carry more than 98% of the domestic telecommunications traffic in the United States; the same percentage is true for other industrialized countries. Optical cables serve as pipelines delivering a tremendous volume of information. Today, the global optical network carries most of the world’s traffic.

• Optical networks operate as a means of transport ferrying information from one point to the other. The scale of operation ranges from intercontinental to continental to metropolitan to local-access networks. Signals from the global network deliver information to our office desks and to our homes.
Light propagation in optical 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.

Note: A core diameter of a singlemode fiber is typically between 8 and 10 µm.
Light propagation in optical fiber

• Step-index fiber: the basic structure

  An optical fiber is a thin, transparent, flexible strand that consists of a core surrounded by cladding. Fig. 3.1 shows this structure and the typical dimensions of optical-fiber components. The core and the cladding of an optical fiber can be 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. The definition of a refractive index, $n$, is rewritten here: $v = c/n$, \( (3.1) \) 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 (Fig. 3.1a), you will immediately understand why this structure is called the step-index fiber.

  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, usually, germanium.

  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 create a light conduit—an optical fiber—that transmits light with—ideally—no attenuation, we must make use of the total internal reflection. 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 center point 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. We usually say that an optical fiber conducts light.
Light propagation in optical fiber

Figure 3.4  Launching light into an optical fiber.
**Light propagation in optical fiber**

- **Total internal reflection**
  - It is important to distinguish between critical incident angle and critical propagation angle. The critical propagation angle, $\alpha_C$, is the angle the beam makes with the center line of the optical fiber. The critical incident angle, $\Theta_1C$, is the angle the beam makes with the line perpendicular to the optical boundary between the core and the cladding. See Fig. 3.4.
  - It is clear that $\alpha_C = 90^\circ - \Theta_1C$. If, for example, $\Theta_1C = 80.57^\circ$; hence, $\alpha_C = 9.43^\circ$. Suppose a beam travels within this optical fiber at $\alpha = 10^\circ > \alpha_C$. Hence, $\Theta_1 = 80^\circ < \Theta_1C$, 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 Fig. 3.4 as a dotted line. 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, $\alpha_C$, 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 less.
  - At this point, it is imperative to bring into our discussion a very important formula: the critical angle of propagation, $\alpha_C$, is determined by only two refractive indexes, $n_1$ (ncore) and $n_2$ (ncladding):
    \[
    \alpha_C = \sin^{-1}\sqrt{1 - \left(\frac{n_2}{n_1}\right)^2}
    \] (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, $\Theta_1C$, 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, $\alpha_C$, with respect to the center line of the fiber, as we’ve already seen.
Light propagation in optical fiber

• 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. Fig. 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 Θa is the incident beam and the beam at angle αC is the launched one, which is the refracted beam with respect to gap-core interface (the reflected beam is not shown here). The formal relationship between Θa and αC can be derived using Snell’s law. From Fig. 3.4 one can find:
  
  $$na \sin \Theta a = n1 \sin \alpha C$$

• If the gap between a light source and a fiber is air, then na is very close to 1 (na = 1.0003). Therefore,
  
  $$\sin \Theta a = n1 \sin \alpha C$$  \hspace{1cm} (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 αC 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 Θa or less.

• It’s clear from Fig. 3.4 that angle Θa is a spatial angle. Light will be saved inside the fiber if it comes from a light source bounded by the cone 2Θa. This is why we call angle 2Θa an acceptance angle. The dotted line in Fig. 3.4 indicates a ray that comes in at an angle exceeding the acceptance angle, Θa, outside the fiber. It is obvious the ray will travel inside the fiber at an angle exceeding the critical propagation angle, αC. This will result in the partial refraction of the ray. In other words, if a ray is not within the acceptance cone defined by 2Θa, it will be lost while traveling inside the fiber.

• Numerical aperture, NA, is: $NA = \sin \Theta a$
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 so because we understand intuitively that the power coming out of the fiber should be less than the power entering it.

\[
\text{Pin (mW)} \quad \text{Pout (mW)} < \text{Pin (mW)}
\]

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.

First, when light is coupled to an optical fiber for the purpose of communication, attenuation 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 of loss of light power within an optical fiber.
Light propagation in optical fiber
Attenuation – bending losses

Figure 3.5 Macrobending loss
Light propagation in optical fiber
Attenuation – bending losses

Figure 3.6  Microbending loss.
• Bending losses.

• **Macrobending loss**
  
  One of the most important advantages of today’s optical fiber is its flexibility, but how much this flexible strand can be bent is our next consideration. Fig. 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, which means that some portion of the beam is escaping the core of the fiber. Hence, the power of the light arriving 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. There is no straightforward method to eliminate this cause of attenuation. The only thing we can do about it is to be cautious when bending an optical fiber.

• **Microbending loss**
  
  The type of loss we discussed above is called “macrobending” loss since it is caused by bending the entire optical fiber. There is another type of loss—“microbending” loss—that is also caused by failure to achieve the condition of total internal reflection. Fig. 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. So 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 center line, or axis, is the imaginary line. *In reality, this line is determined by the core-cladding geometry.*

• **Microbending: Its Origin and Improving Its 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.

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

Figure 3.7 Scattering loss – main cause of loss in optical fiber.
• Scattering.
  
  Suppose there is an imperfection in a core material, as shown in Fig. 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, based on this fact, 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 Fig. 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 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.

• Scattering is the major cause of light power loss within an optical fiber.
Light propagation in optical fiber

Figure 3.8  Typical spectral attenuation caused by absorption.
Absorption.

Basic mechanism

You will recall 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. Remember, too, that we learned that we cannot change the energy levels of the material. They have been predetermined by nature. What we can do, though, to reduce or eliminate absorption is change either the light frequency, f (which means to change a proton’s energy, Ep), or work with another material (which means to change the value of the energy levels and, thus, the energy gap). Remember that changing the light frequency, f, means also changing the light wavelength, λ, since λf = 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, which is shown in Fig. 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. By transparent, we mean that it 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 fabrication process and it is very hard to eliminate them. OH- molecules have major peaks of absorption at 945, 1240, and 1380 nm. (See Fig.3.8.)

This picture was true for the first-generation fiber fabricated more than twenty years ago. Today, manufacturers manage to produce an optical fiber with almost zero absorption peaks!
Enhanced singlemode optical fiber (E-SMF) exhibits no absorption peak in contrast to SMF.
Light propagation in optical fiber
Attenuation - calculations

- **Calculations of total attenuation**
- Fiber loss is the ratio of power at the output end of a fiber, $P_{out}$, to power launched into the fiber, $P_{in}$.
- $\text{Loss} = \frac{P_{out} (\text{W})}{P_{in} (\text{W})}$
  \hspace{1cm} \text{(3.9)}
- In communications technology, we measure loss in decibels (dB), which relate to measurements in watts as follows:
- $\text{Loss (dB)} = 10 \log_{10} \left( \frac{P_{out} (\text{W})}{P_{in} (\text{W})} \right)$
  \hspace{1cm} \text{(3.10)}
- Since $P_{out}$ is always less than $P_{in}$ (because we consider “attenuation,” but not “amplification”), $\log_{10} \left( \frac{P_{out}}{P_{in}} \right)$ is always negative.
- 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 $\text{Loss}_1 = -20 \text{ dB}$ and for another fiber $\text{Loss}_2 = -30 \text{ dB}$, 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, $A$.
- $A (\text{dB/km}) = -\text{loss (dB)}/\text{fiber length (km)}$
  \hspace{1cm} \text{(3.11)}
- This quantity, $A (\text{dB/km})$, 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. To make the result of the calculations (attenuation, that is) the positive number, the negative sign is used as Formula 3.11 shows. This is accepted practice in telecommunications industry.
From definition of attenuation given in Formula 3.11, it is easy to derive the following formula:

\[ P_{\text{out}}(W) = P_{\text{in}}(W) \times 10^{-A(\text{dB/km})L(\text{km})/10} \]  
(3.12)

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 \( P_{\text{in}} \) is 1 mW and \( A_L = -3 \) dB. Then \( P_{\text{out}} = P_{\text{in}} \times 10^{-0.3} = 0.5 \) mW, which means that absolute attenuation equals \( P_{\text{out}}/P_{\text{in}}, \) or 0.5. If \( A_L = -10 \) dB, then \( P_{\text{out}} = P_{\text{in}}/10, \) and so forth. On the other hand, if you know \( P_{\text{in}} \) and \( P_{\text{out}}, \) you can find the loss in dB. For example, if \( P_{\text{in}} = 1 \) mW and \( P_{\text{out}} = 0.001 \) mW, then \( A_L = -30 \) dB, and so on.

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

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

\[ L = \left(10/A\right) \log_{10}\left(P_{\text{in}}/P_{\text{out}}\right) \]  
(3.13)

Formula 2.13 allows us to calculate the maximum transmission distance imposed by attenuation, bearing in mind that the minimum value of \( P_{\text{out}} \) is determined by the sensitivity of the receiver.
Light propagation in optical fiber

Attenuation - spectral

Figure 5.7  Spectral attenuation curves of singlemode and multimode fibers. (Courtesy of Corning Inc. Adapted from data sheets for the SMF-28 singlemode and 62.5/125 multimode fibers.)

Note that modern singlemode fiber doesn’t have an absorption peak of attenuation.

Attenuation of a MM fiber is greater than that of a SM fiber because higher order modes experience more scattering, absorption, and bending events.

Attenuation of a modern SM fiber is as small as 0.2 dB/km→ Power of an output signal decreases only 100 times every 100 km.
Light propagation in optical fiber

Attenuation - measurement


Setup for measuring attenuation in an optical fiber.
• Distinguish between loss in dB and attenuation in dB/km.
• There is a device called a power meter that allows us to measure the power of light. The result is displayed in dBm, which is a specific unit of power in decibels when the reference power is 1 mW:
  \[ 1 \text{ dBm} = -10 \log(\text{Pout}/1\text{mW}) \]  
  (3.10a)
• A diagram of an experimental arrangement for an attenuation measurement is shown in Slide 26. This setup follows the fiber-optic test procedure (FOTP) # 15 as specified by Telecommunications Industry Association (TIA). First, determine input power (reference point with patch cord. To do so, connect a light source and a power meter, using two patch cords and ST adaptor. This measurement gives you \( \text{Pin} \). Keep the patch cords connected to the light source and the power meter for the all measurements. Secondly, connect a fiber under test between two patch cords, using two ST adaptors. This measurement gives you \( \text{Pout} \). Measure \( \text{Pout} \) for all the available fiber-optic cables.
• The key point here is this: Since fiber connections to the source and to the power meter inevitably introduce additional losses, you want to leave these connections undisturbed when you change the fiber under test.
• It is evident that we can measure a fiber loss. To calculate loss in dB when obtaining readings in dBm, use the following obvious formula:
  \[ \text{Loss (dB)} = \text{Pin (dBm)} - \text{Pout (dBm)} \]
• Be careful about signs; always remember that you want to present the fiber loss as a positive number. For example, if your readings are \( \text{Pin} = -1.0 \text{ dBm} \) and \( \text{Pout} = -1.5 \text{ dBm} \), the fiber loss is 0.5 dB.
• To calculate attenuation based on your measurement, measure the fiber length and use Formula 3.11.
Module 2: Assignments

• See reading assignment and homework problems in the course’s outline.
• After study this module you must be able to:
  – Explain the basic structure of a step-index optical fiber along with main dimensions of multimode and singlemode optical fibers.
  – Sketch and explain the refractive index profile of a step-index fiber. Explain how we achieve total internal reflection within an optical fiber.
  – Sketch diagram and explain how we must launch light into a fiber to achieve total internal reflection. Relate numerical aperture to a propagation angle.
  – Explain the phenomenon of power loss within an optical fiber.
  – Explain three main mechanisms of power loss in optical fiber.
  – Describe the recent developments in manufacturing optical fibers regarding absorption peaks in fiber attenuation.
  – Discuss spectral attenuation of singlemode and multimode fibers.
  – Calculate power loss and attenuation in optical fiber.
  – Calculate maximum transmission distance in optical fiber.
  – Explain measurements of power loss and calculations of attenuations when the measurement results are given in dBm.