Bringing the Spirit of Industry into the Engineering-Technology Classroom

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ABSTRACT

An engineering-technology program requires—by its very nature—students to be comfortable with industry standards and practices. One of the ways to achieve this goal is incorporating industrial documents into the teaching material. This paper describes an example of this approach: studying the properties of a multimode optical fiber, MMF, in an optical-communication course based on industrial documentation.

Teaching MMF is particularly tricky because industry documentations contain only MMF specifications without explanations of the physical mechanisms that underlie these specifications. What's more, these mechanisms can't be investigated by direct measurements in a laboratory. Needles to say, engineering-technology students must know these mechanisms to comprehend the existing industry developments and to find the solutions to the technical problems that will arise in the future. This paper demonstrates how our approach to teaching the topic enables us to connect every specification given in industry documents with the mechanism of an MMF operation.

STATEMENT OF THE PROBLEM

Imagine you are a newly hired technologist, fresh from college with a bachelor's degree in telecommunications technology. Your supervisor assigns you to choose an MMF vendor because your responsibility is to install a local area network – a new project your company is involved in. Surely, you go to the Internet, find several available manufacturers and try to compare the specifications of their optical fibers. You certainly remember from your college course in optical communications that you need to look first at the two main characteristics of an optical fiber: attenuation and bandwidth. You try to understand the data on these characteristics presented in the manufacturers' specifications sheets and, unfortunately, you get confused. Why is attenuation given with the remark "Maximum Value"? Is attenuation a constant number or does it vary below its maximum value? Why is bandwidth specified in *MHz-km* units when you have learned that bandwidth is a range of frequencies and, therefore, must be measured in hertz? Why does one manufacturer specify *overfilled bandwidth* while another refers to *legacy performance*? You will certainly have many questions of this nature when you start your professional work.

To better prepare our graduates for their professional career, we must rely on using and discussion the industrial documentation. This paper describes an example of this approach: studying the properties of a multimode optical fiber, MMF, in an optical-communication course based on industrial documentation. The importance of MMF to modern optical communications can't be overestimated. Thanks to relatively inexpensive terminal opto-electronic equipment, MMF-based communications systems have become the main transmission means in short-reach networks. The vast majority of the today's LANs use MMF as a transmission medium. Recent dramatic improvements in transmission properties of MMF make it a medium of choice for an even wider spectrum of applications. This is why this topic plays a significant role in our fiber-optic communications course.

Teaching MMF is particularly tricky because industry documentations contain only MMF specifications without explanations of the physical mechanisms that underlie these specifications. What's more, these mechanisms can't be investigated by direct measurements in a laboratory. Needles to say, engineering-technology students must know these mechanisms to comprehend the existing industry developments and to find the solutions to the technical problems that will arise in the future. Much of this information can be obtain from research publications, but connecting research and teaching approaches is not an easy task [1]. Our approach to teaching the topic enables us to connect every specification given in industry documents with the physics of an MMF operation.

Our experience in teaching MMF includes (1) traditional theoretical segment, where we explain the physical mechanisms underlying the properties of an MMF, (2) hands-on and computer-simulation measurements of these properties, and (3) an analytical segment, where we connect the results of our measurements with the physical mechanisms discussed in the theory segment. This approach to teaching the topic enables us to connect every specification given in industry documents with the physics of an MMF operation.

The paper is organized as follows: We present a short theory of MMF operation and simultaneously demonstrate our approach to teaching the subject in an engineering-technology program; in conclusion, we refer to our teaching experience and discuss our achievements and problems that still remain.

TEACHING ATTENUATION AND BANDWIDTH OF MMF

Optical fiber—a strand of glass thinner than a human hair—is today a main component in transmitting information: from one point on the globe to another irrespective of distance. There are two basic types of optical fiber in use: multimode fiber (MMF) and singlemode fiber (SMF). An MMF is a medium that carries information a short distance (from 100 meters to 2 km) and an ultra-short distance (from centimeters to tens of meters). All other distances are covered by an SMF.

The main advantages of MMF over traditional copper-based media are greater transmission capacity (bandwidth), longer transmission distance, and immunity to electromagnetic (EM) interference. All these factors result in a better signal at the output devices, such as computers, speakers or TV screens.

Optical fiber is a transmission medium, as illustrated in Figure 1. Its main function is delivering either a digital signal in the form of optical pulses, as in most cases of optical communications, or an analog optical signal in the form of amplitude-modulated signals, as is still the case in cable-TV transmission.

As with any transmission medium, in optical fiber we are concerned with the distortion of an output signal. This distortion shows up as a decrease in power, caused by losses, and the broadening of the output pulse, caused by dispersion. Power diminution restricts transmission distance and pulse widening limits the bandwidth of optical fiber. The decrease in signal power is described by the fiber *attenuation* and the pulse widening is characterized by the fiber *transmission bandwidth* (*capacity*). Figure 1 shows the degradation of an output pulse. These basic characteristics depend on the operating wavelength. Light sources radiating at 850 nm and 1300 nm are used with MMF.

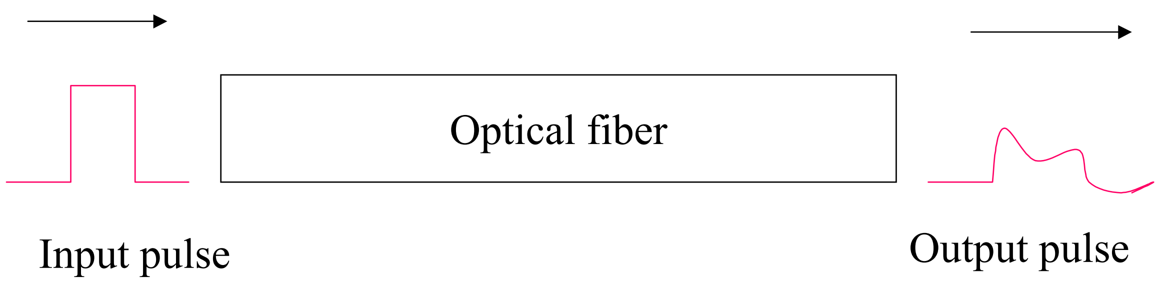


Figure 1. Optical fiber is a transmission medium

Why does the optical pulse lose its power and spread while traveling down the fiber? To answer this, we need to consider how MMF is built and how this fiber conducts light.

MMF structure: An optical fiber consists of a core with a diameter equal to either 62.5 μm or 50 μm surrounded by a cladding with a diameter equal to 125 μm. They are made from the same material—glass, in fact—but differ in their refractive indexes. The core must have higher value of a refractive index than the cladding has, as shown in Figure 2; we call such a fiber step-index (SI) MMF. The core refractive index may also change gradually, so that it is high at the center and low (equal to the cladding index) at the core-cladding interface. (See Figures 3 and 6.) This type of fiber is called graded-index (GI) MMF; only GI MMF is used in practice. (For more detailed explanations of the MMF operation, see [2].)

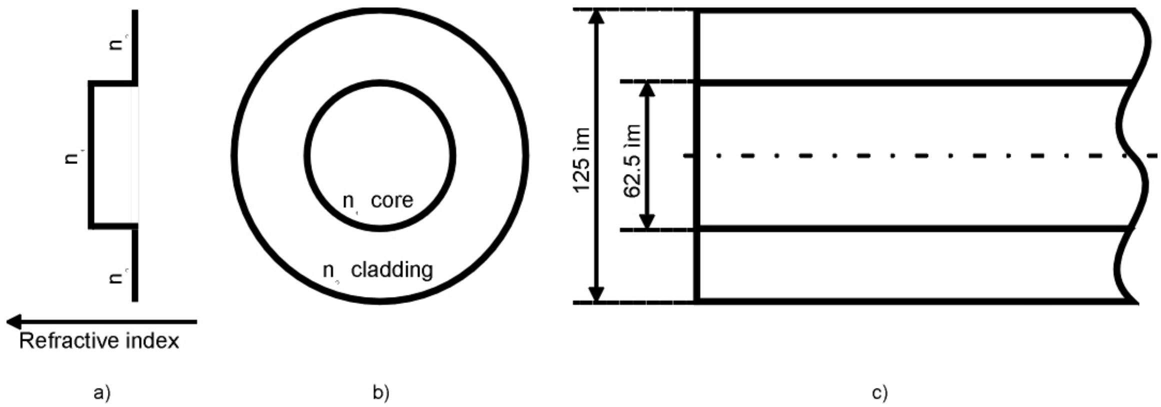


Figure 2. Basic structure of an MMF: a) profile of a refractive index; b) refractive indexes of a core and a cladding; c) cross-section of an MMF [2].

Modes: When entering a fiber core, continuous light travels within the core at distinctive, separate paths, as required by resonant conditions. We usually consider these paths as discrete beams called modes. The beam (mode) traveling along a fiber centerline is designated a zero-order (fundamental) mode; the highest-order mode is termed the critical mode. Between them, hundreds and even thousands of intermediate-order modes exist. These beams (modes, that is) propagate differently in step-index and graded-index MMFs, as shown in Figure 3.

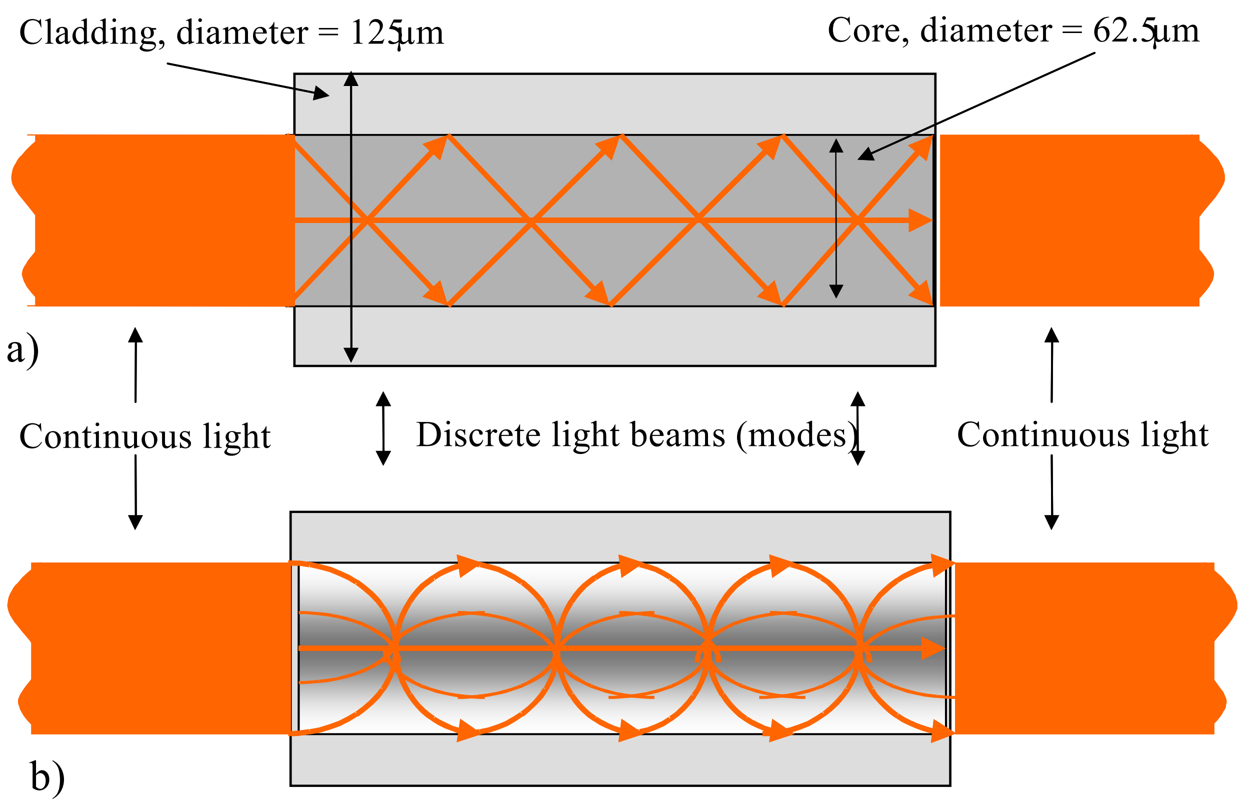


Figure 3. Modes in a multimode fiber: a) Step-index MMF; b) graded-index MMF.

Attenuation: The main mechanism of power loss is scattering light at the irregularities of the core's refractive index. The other contributors are absorption and bending losses. The longer the light travels within a core, the greater the number of scattering, absorption, and bending events that occur and the higher the loss. It is plausible to assume that the losses are proportional to the distance of light propagation:

$$\text{Loss} = \text{K x Length (km)}, \quad (1)$$

where *K* is a constant. Thus, if we divide total losses by a fiber's length, we will obtain an objective measure of the fiber's quality called *attenuation, A*, which is measured in decibels per kilometer (dB/km):

$$A \text{ (dB/km)} = \text{-Loss (dB) / Fiber length (km)}, \quad (2)$$

where the negative sign is used in order to obtain attenuation as a positive number, according to standard industry practice.

If we plug Formula 1 into Formula 2, we obtain

$$A \text{ (dB/km)} = \text{-Loss (dB)/Length (km)} = - K \text{ x Length (km)/Length (km)} = -K.$$

Introducing $C = -K$, we obtain

$$A \text{ (dB/km)} = C. \quad (3)$$

Thus, attenuation should be a constant number; this is why we use attenuation as a characteristic of fiber-loss properties. Teaching MMF attenuation: After introducing the theory of attenuation preceded by a discussion of loss mechanisms in MMF, we arrange the measurement of attenuation in MMF [3]. It should be noted that these hands-on exercises are performed according to the industry standards that a manufacturer refers to in its specifications [4], [5]. Typical result of such a measurement is shown in Figure 4.

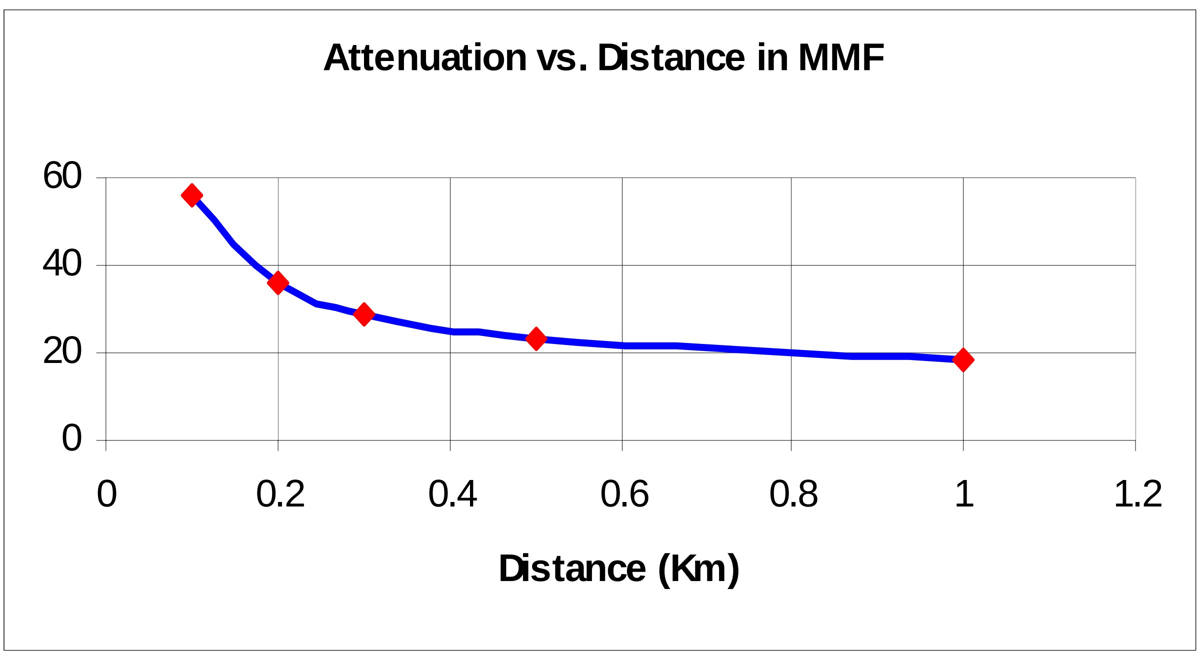


Figure 4. Measured MMF attenuation vs. distance. (Student Pedro Rojas, course TC 700, Spring 2004.)

The students have to explain why the measured attenuation decreases with distance while theory predicts that attenuation should be constant, as Figure 5 shows. While developing these explanations, students inevitably should come to the conclusion that the only reason for this discrepancy is the existence of modes in MMF. In other words, an experimental result proves that, indeed, continuous light is broken down in a set of separate beams (modes) within an optical fiber, as predicted by theory. (See Figure 3.)

To understand the physical mechanism underlying this phenomenon, students have to study this topic in more depth. We usually refer them to the course textbook [2].

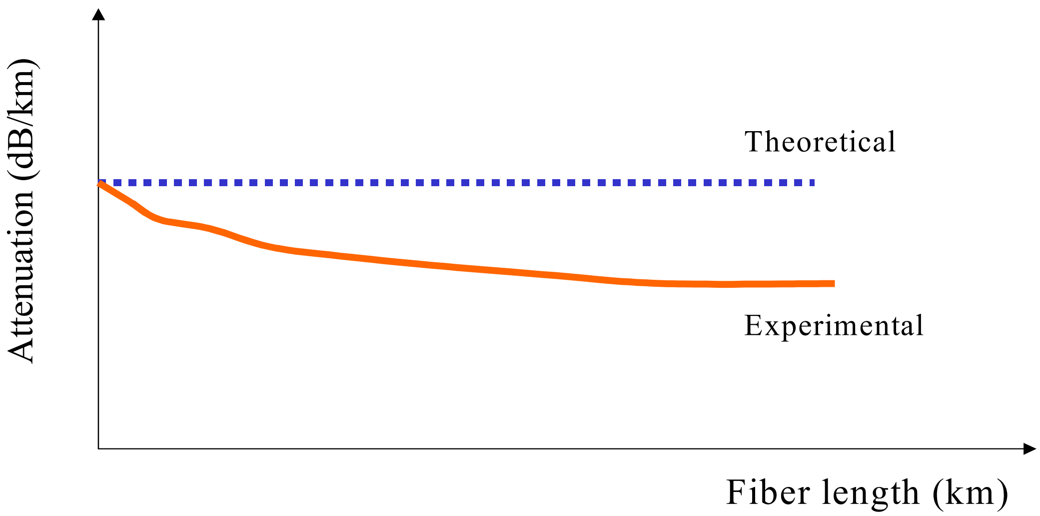


Figure 5. Conceptual view at attenuation in MMF.

Thus, teaching MMF attenuation includes both theoretical and experimental segments. We place our main emphasis on the fact that experimental results (attenuation decreases with distance) contradict the theoretical predictions (attenuation should be constant). Students must analyze this contradiction and develop explanations for it. To help students develop their reasoning, we ask them to answer to the following set of questions:

- Should losses increase with an increase in fiber length? Should losses theoretically be directly proportional to fiber length? Why? Are they?
- Should attenuation theoretically be independent of the fiber length? Why? Is it?
- Why does attenuation change as the length of a fiber changes?
- How do modes affect attenuation in optical fiber?
- Did this experiment prove the existence of modes in MMF? Explain.

We also ask students to follow the logic of this study: Objectives (existence of modes) ➔ theory (modes exist and affect attenuation) ➔ expected results (attenuation changes in MMF due to the presence of modes) ➔ experimental results (attenuation in MMF decreases with an increase in fiber length) ➔ comparison of expected results, experimental results and the manufacturer's data.

Typically, students develop the following reasoning for explaining the change of MMF attenuation with distance: To understand the discrepancy between theory and experiment, we need to refer to Figure 3, which clearly shows that the zero-order mode and the critical mode travel different distances within the same fiber; therefore, they experience different losses. In deriving Formula 3, we assumed that the *fiber length* and the *propagation distance* were the same, but, in general, they are not. This assumption is true only for the fundamental mode. This is why attenuation in a singlemode fiber, where only the fundamental mode exists, should be a constant number. Since the highest-order modes in MMF travel the longest distances, they experience the greatest losses: thus, these modes will disappear after traveling over a short fiber length. Then, the next higher-order modes will disappear followed by the next ones and the ones after that in succeeding order, the process continuing until only the lower-order modes remain. There are two consequences of this consideration: First, attenuation must change with fiber length and the shorter the length, the higher the attenuation because more modes exist within a fiber. Secondly, as fiber length increases, a steady state, when only the lower-order modes remain, should be reached. Indeed, such a state exists. It is called *equilibrium mode distribution (EMD)*. Under this condition, the total light beam will concentrate around the fiber axis. Starting from the point where EMD is achieved, the attenuation of an MMF becomes almost constant.

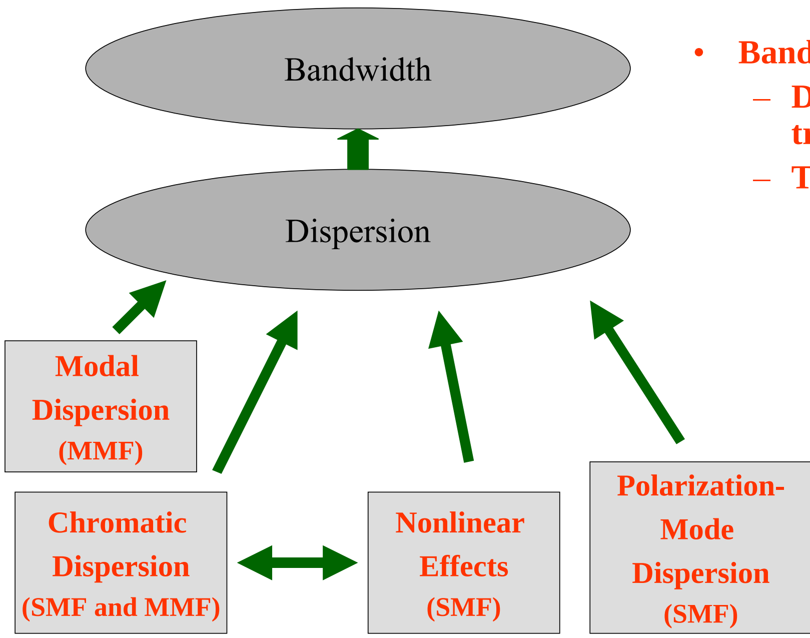
The fact that attenuation in an MMF changes with respect to fiber length is proof that modes do exist. Since we can't arrange for direct observation of modes within a fiber, this indirect observation proves the existence of modes in MMF.

Manufacturers specify attenuation of their fibers at the lowest (that is, the best) value. In fact, when measuring attenuation, manufacturers take special measures to strip off the higher order modes and achieve an EMD condition. Ironically, manufacturers call these figures "maximum values." Typical "maximum" values of MMF attenuation are 2.5 dB/km at 850 nm and 0.7 dB/km at 1300 nm.

Bandwidth: In telecommunications, we use the term bandwidth almost exclusively in the sense of transmission bandwidth, which is determined by the highest frequency of the transmitted signal. The greater the transmission bandwidth, the faster the transmission. Therefore, the transmission bandwidth must cover the highest frequency of the transmitted signal—this is a necessary condition—but the bandwidth can be greater than that frequency, a factor that improves transmission conditions.

Bandwidth is a range of frequencies and it is always measured in hertz. Therefore, strictly speaking, *the term bandwidth can be applied only to analog transmission.* However, today telecommunications specialists use the term in a much broader sense, for example, as a measure of the transmission capacity of any type of link—analog or digital. This loose usage has become industry practice.

Bandwidth of MMF: Bandwidth (transmission capacity) of an MMF has three distinguish features: First, it is determined by dispersion, which, in turn, includes several phenomena, as shown in Figure 6.



- **Bandwidth:**
  - **Definition Bandwidth = transmission capacity**
  - **The usage of the term:**
    - **Transmission capacity given as BW x L in MHz-km or bit/s x km or bit/s.**
    - **Wavelength window given in nm or THz within which fiber can conduct light at acceptable attenuation.**

Figure 6. Bandwidth of an optical fiber: general view [6].

Secondly, as the documents [4] and [5] show, manufacturers use the term *bandwidth* to describe bandwidth-length product, which is a true measure of the transmission capacity of any transmission medium. Third, the term *bandwidth* in optical communications also refers to a wavelength window, given in nm or in THz, within which an optical fiber can conduct light at an acceptable attenuation. Let's discuss these bandwidth features in sequence.

Modal dispersion: Optical fiber has entered the telecommunications world as a transmission medium that has promised unlimited bandwidth. Yet, network engineers found very quickly that the bandwidth of the first MMFs did not exceed by very much the bandwidth of a coaxial cable. This is because the total power of an input optical pulse, carried by individual modes, is delivered inside the fiber in small amounts. Since these modes travel different distances within a fiber, they arrive at the destination point at different times, which results in the spreading of an output pulse. This phenomenon is known as intermodal, or modal, dispersion. These explanations are visualized in Figure 7.

It is modal dispersion that severely limits the bandwidth of an MMF because transmission capacity (bandwidth) is inversely proportional to pulse width. All other dispersion causes, shown in Figure 6, play minor roles in restricting the MMF bandwidth.

Since modal dispersion results in a pulse spread, which, in turn, leads to restriction of the MMF bandwidth, we can say that the bandwidth of a MMF is determined by modal dispersion.

The difference in arrival time among modes within a pulse is referred to as differential mode delay (DMD). This parameter is a measure of modal dispersion in regard to the MMF bandwidth.

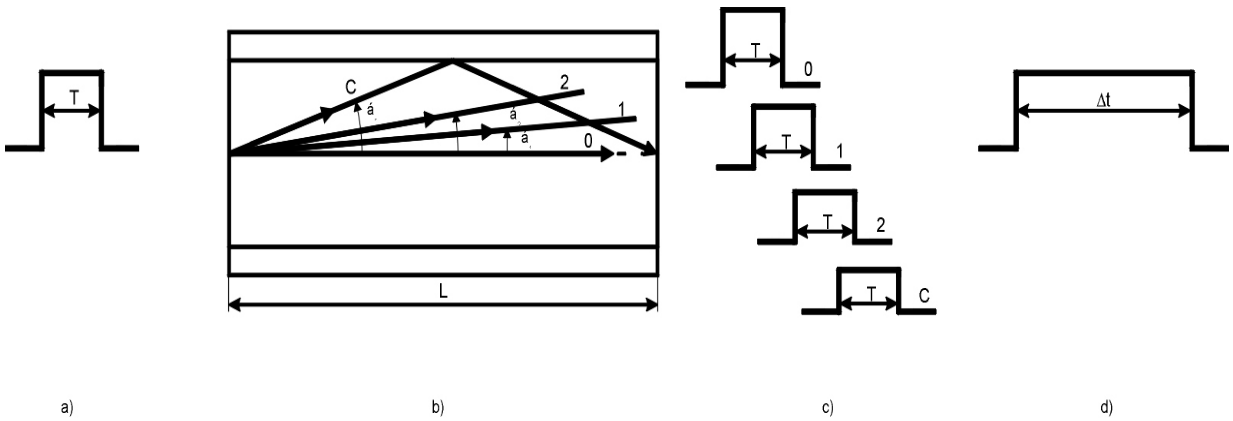


Figure 7. Mechanism of modal dispersion [2].

Dispersion in general—and modal dispersion in particular—appears as a spread of optical pulse in time domain. Since pulses become wider, fewer of them can be accommodated within a given time; therefore, fewer pulses can be transmitted per second. Eventually, modal dispersion results in severe intersymbol interference (ISI), which makes the recovery of information impossible. This is how dispersion restricts bit rate. The actual dispersion process is presented in Figure 8.

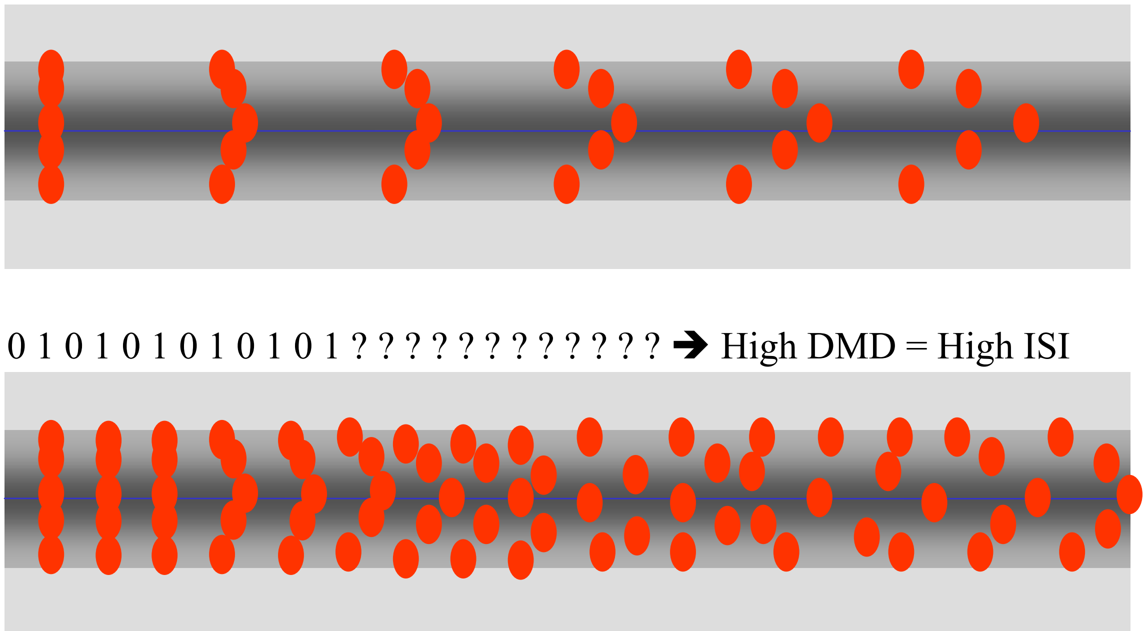


Figure 8. Modal dispersion: a) the concept; b) modal dispersion and bandwidth [7].

Teaching MMF bandwidth: After studying the bandwidth theory, students have to perform experiments. In these exercises, we rely on computer simulation by using a specialized software package called LinkSim. It was developed by RSoft Corporation. The typical results of such an experiment is presented in Figure 9. Four graphs in Figure 9 show the transformation of pulses transmitted through an MMF over a given fiber length.

By analyzing the results of their experiments, students come to understand that the theory they've studied is true and, indeed, optical pulses get spread within an MMF, as shown in Figures 7 and 8. Since we can't perform direct measurements of a pulse spread within an optical fiber, this indirect proof, based on analysis of the experimental results, is an important concept that engineering-technology students must be familiar with.

Now students comprehend the point that the bandwidth of an MMF is very restricted and one of the fundamental concepts of telecommunications—bandwidth-length product—has to be applied. This concept states that there is a trade-off between bandwidth, BW, and length, L. In other words, the bandwidth-length product for a given transmission medium is a constant, as Formula 4 shows. This is why manufacturers specify MMF transmission capacity as a bandwidth-length product.

$$BW\ (Hz) \times L\ (km) = \text{constant} \qquad (4)$$

Based on this study, students now are able to understand the section of manufacturers' specifications sheets titled *Bandwidth* [4] or *Transmission Characteristics* [5].

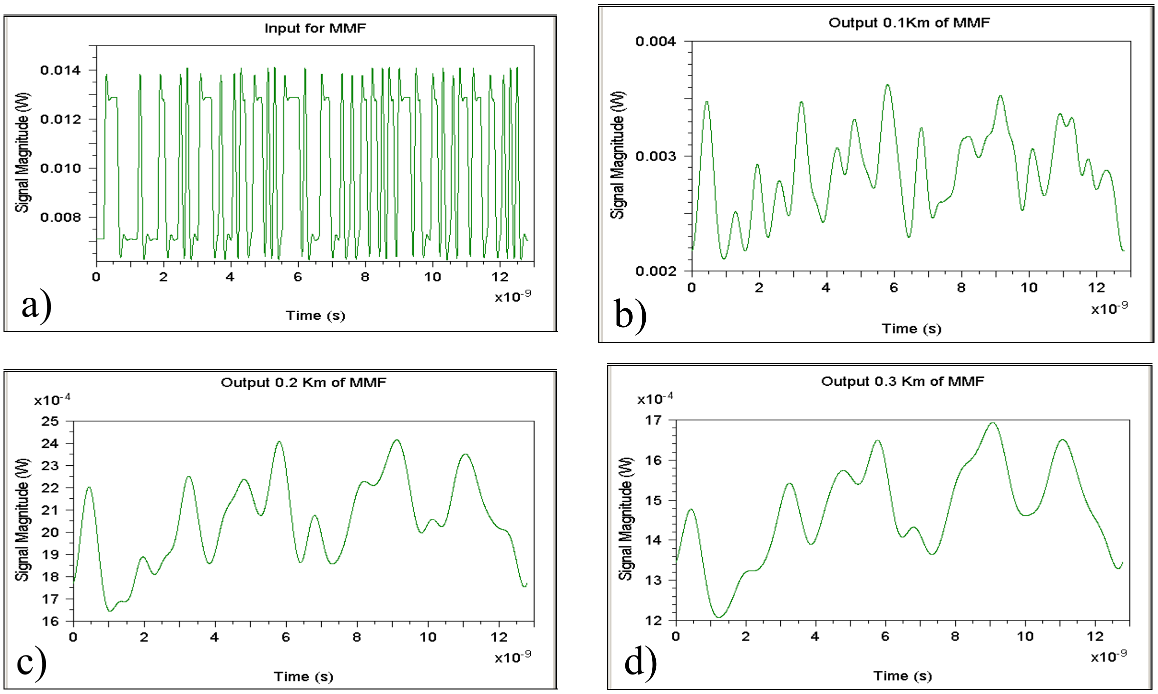


Figure 9. Pulse spread in MMF caused by modal dispersion: a) train of input pulses; b) the same train after transmission over 100 meters; c) after 200 m; d) after 300 m. (Computer simulation using LinkSim by RSoft, Inc.; student Pedro Rojas, course TC 700, Spring 2004.)

Solutions to modal-dispersion problem: The initial solution to the modal-dispersion problem was developing a graded-index MMF (Figure 3). Indeed, since the core's refractive index changes from high at the center to low at the cladding border, the beam traveling along the center (the shortest distance) will propagate more slowly than the beam traveling along the border (the longest distance). Thus, these two modes should arrive at the destination point more or less simultaneously. (Students have to recall that velocity, *v*, of light within a medium is given by $v = c/n$, where c = 3 x 108 m/s is the speed of light in a vacuum and *n* is a medium's refractive index.) The fact is the bandwidth of a GI MMF is much better than that of an SI MMF.

Multimode fiber (MMF) and singlemode fiber (SMF): If all the problems of an MMF stem from the multimode nature of its operation, why don't we simply get rid of these modes? Yes, singlemode fiber exists and today it is the main transmission medium that wires the entire globe. To restrict the number of modes to one, the core diameter of an SMF is reduced to eight to 10 μm, which results in the much higher cost of transmitters, receivers, and other opto-electronic and optical devices. Indeed, instead of a $5 LED, one needs to use a $5,000 laser in transmitters. Coupling light in and out of the SMF requires better quality (read, expensive) components and precise alignments at every step of SMF usage. Thus, the lower attenuation (typically, 0.2 dB/km at 1550 nm) and virtually unlimited bandwidth of an SMF come with the much higher price of telecommunications links. Figure 10 presents the general view at dispersion in SI MMF, GI MMF and SMF.

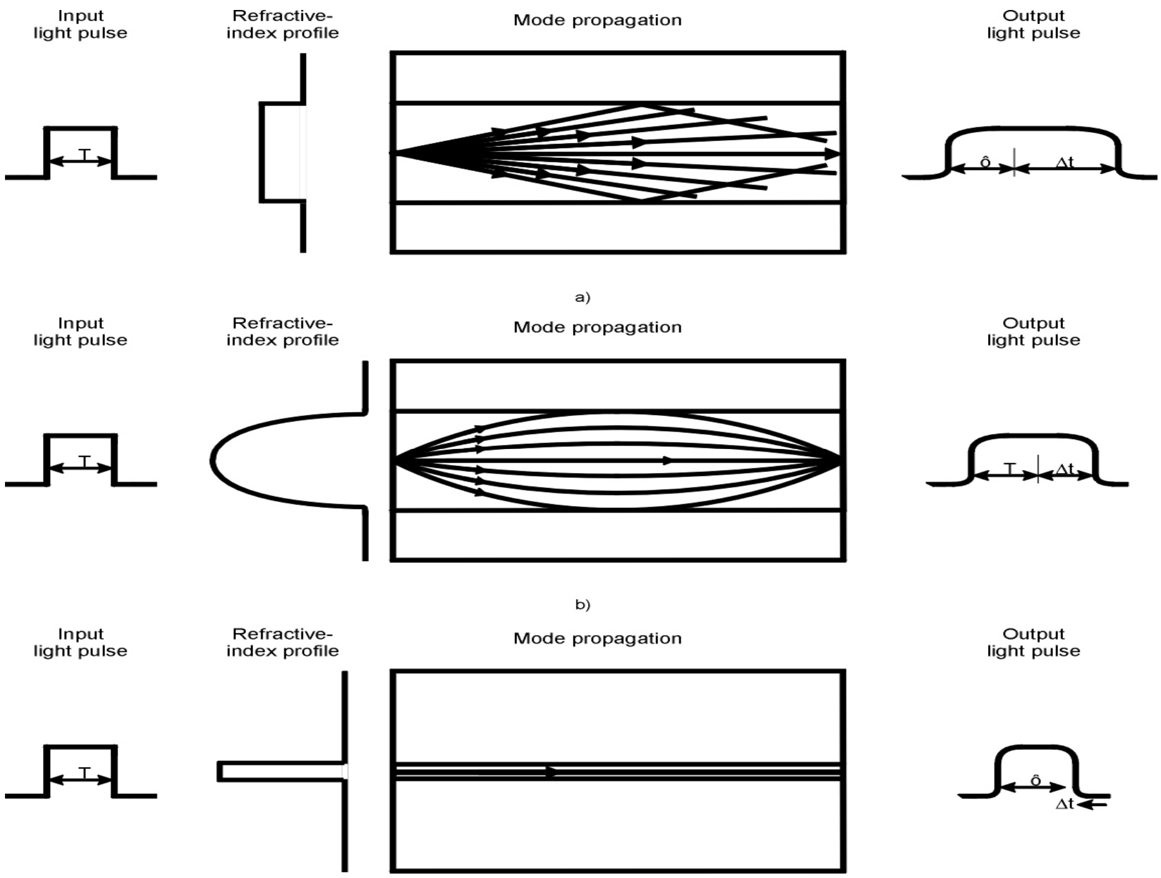


Figure 10. Dispersion in a) step-index (SI) MMF, b) graded-index (GI) MMF and c) singlemode fiber (SMF) [2].

Vertical-cavity surface-emitting laser (VCSEL): Fortunately, recent developments have brought about a new type of light source—the vertical-cavity surface-emitting laser, VCSEL—that combines the excellent characteristics of light produced by a laser with a low manufacturing cost associated with an LED. VCSEL generates a well-directed beam in contrast to the widespread beam produced by a traditional LED, which results in exciting fewer modes within an MMF without changing the fiber's mechanical dimensions, as shown in Figure 11. At the same time, a VCSEL costs about $25, which is slightly higher than the cost of LED but much lower than the cost of a long-distance laser. The VCSEL radiates at 850 nm, the wavelength at which all short-reach fiber-optic links operate.

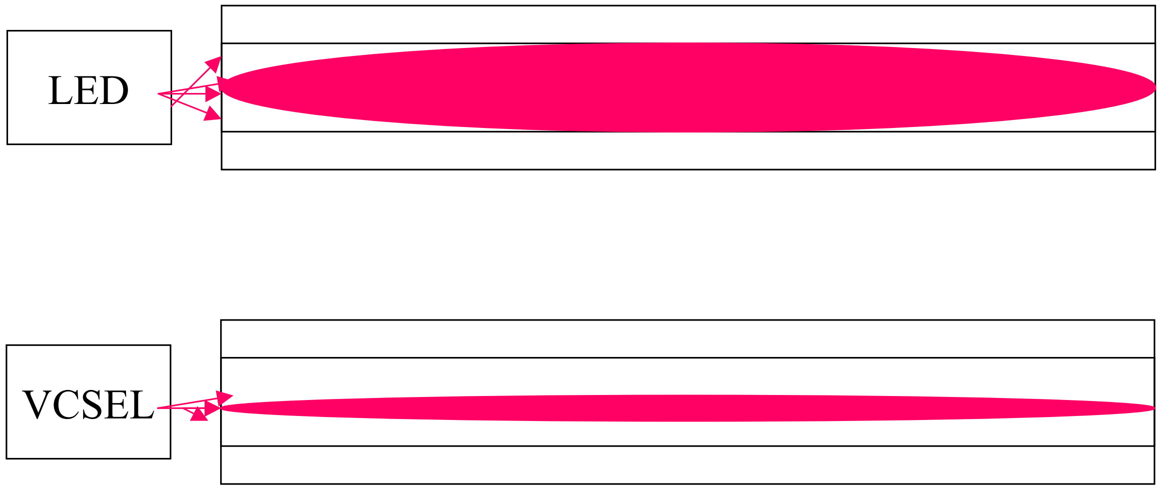


Figure 11. Launching light into an MMF from a) an LED and b) a VCSEL.

Analyzing Figure 11, students can easily comprehend the terms *Overfilled* (Figure 11a) and *Laser* (Figure 11b) in *Minimum Bandwidth Specifications* that manufacturers routinely use [5].

Teaching this subject requires theoretical and experimental studies of the main characteristics of LEDs and VCSELs and hands-on measurement of MMF attenuation with different LEDs and VCSELs. The students must answer a simple question: Why does attenuation change differently with fiber length when measured with LEDs and with a VCSEL? The answer, of course, involves, again, understanding the effect of modes on an MMF operation.

MMF: latest developments: It appears that the conventional MMF manufactured for the last fifteen years doesn't work well with a VCSEL because its refractive-index profile has deficiencies at the center of the fiber core, where the VCSEL beam is concentrated. Addressing this challenge, manufacturers now produce a new type of MMF with an excellent refractive-index profile. Conventional and new MMFs are shown in Figure 12. In addition, the new type of MMF is being produced with a core diameter equal to 50 μm, which reduces the number of modes These improvements result in the ability of the new MMF to deliver 10 Gbit/s over 300 meters. Since there is a trade-off between bandwidth and transmission distance, one can transmit a lower bit rate over a longer distance. For example, this new MMF can carry 1 Gbit/s over 2 km. Putting it another way, the bandwidth-length product of the new MMF improves tenfold and typically equals 4000 MHz-km at 850 nm. (See [4] and [5].) These very impressive characteristics allow network designers to build new types of local, including home, networks.

The very latest advances in developing MMF include laser-optimized multimode fiber. Manufacturers manage to reduce pulse spread so dramatically that the modern MMF can carry 10 Gbit/s of traffic over a significant (550 meters!) distance. Figure 13 shows the reduction of a pulse spread in a laser-optimized MMF compared pulse-spread reduction in a conventional MMF. Studying these results allows the students to understand why manufacturers refer to *Legacy Performance* versus *High Performance* in the bandwidth section of their MMF specifications [5]. Clearly, *Legacy Performance* refers to the bandwidth of a conventional MMF, while *High Performance* refers to the operation of a newly developed MMF.

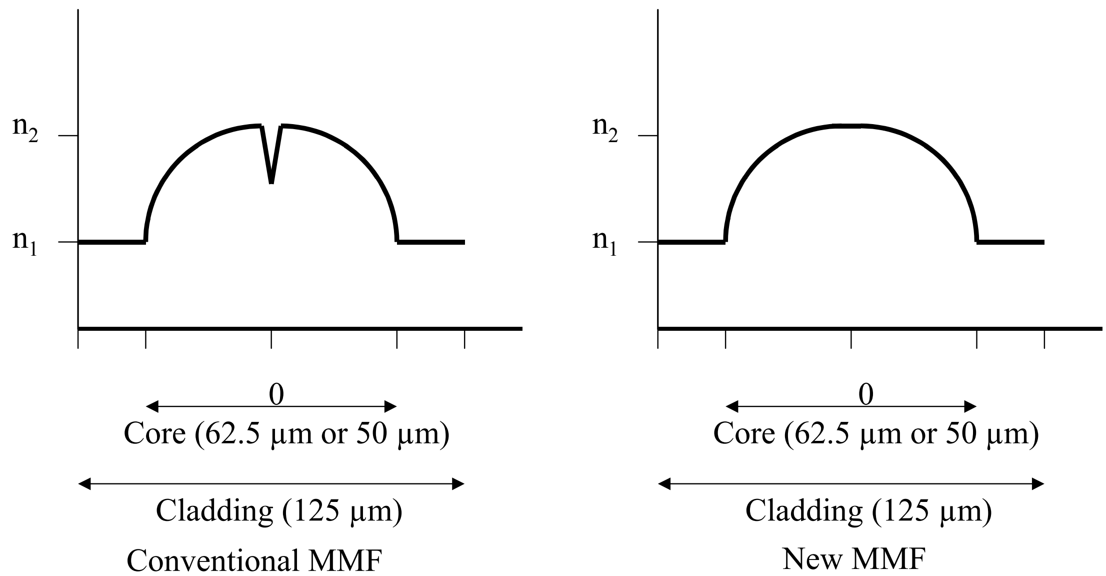


Figure 12. Refractive-index profiles of a) conventional MMF and b) new MMF. Legend: n_1 is the cladding's refractive index; n_2 is the maximum value of a core's refractive index.

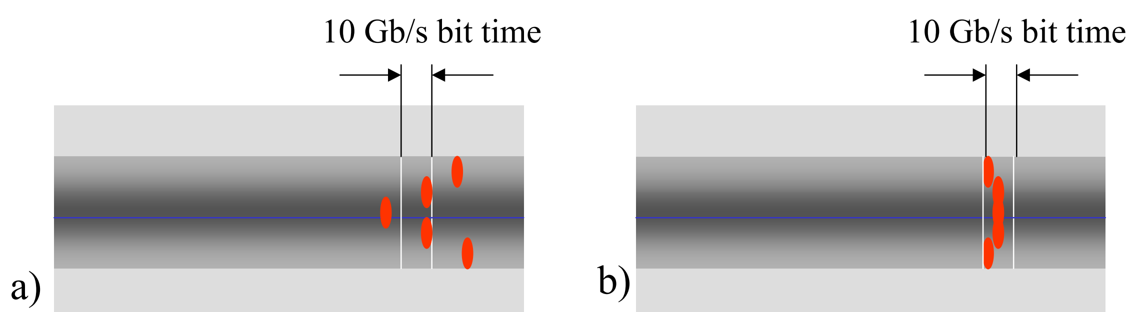


Figure 13. Received pulse at 10 Gb/s in (a) conventional multimode fiber and (b) laser-optimized multimode fiber. [8].

The latest achievement announced recently carries impressive numbers, such as bandwidth-length product is equal to 4700 MHz-km and the transmission length for 10 Gbit/s traffic is equal to 550 meters. (Source: "LaserWave™550/300 Fibers" OFS, Marketing Communications Fiber 115-0305, 2005.)

ANALYSIS OF TYPICAL SPECIFICATIONS OF MMF

Typical optical characteristics of modern multimode fiber optimized for 10-Gb/s performance are presented in the following table.

Core diameter (µm)	50 ± 2.5
Cladding diameter (µm)	125 ± 1.0
Attenuation at 850 nm (dB/km)	≤ 2.4
Overfilled bandwidth at 850 nm (MHz-km)	≥ 3500/1500
Laser bandwidth at 850 nm (MHz-km)	≥ 4700/2000
Gigabit/10 Gigabit Ethernet distance at 850 nm (meters)	550/320
Zero dispersion wavelength range (nm)	1297 – 1316
Maximum dispersion slope (ps/nm^2•km)	0.101
Group refractive index at 850 nm	1.483

Sources: Specifications of LaserWave™550/300 Fibers from Furukawa Electric North America (OFS) and InfiniCor by Corning Inc. (See www.ofsoptics.com/ofs-fiber and www.corning.com)

In their laboratory reports and term projects, the students must present an analysis of this table or of the optical specifications found in the manufacturers' data sheet shown in [4] and [5]. In addition, quizzes and final examinations also include questions based on these technical documents.

CONCLUSION

After studying all this material both theoretically and experimentally, our students become comfortable with using and interpreting the manufacturers' technical documentation, which is a major goal of this approach. Presenting and discussing the effect of modes on MMF attenuation and bandwidth in various forms result in a good understanding of this subject by our students. On the other hand, limited equipment and teaching hours prevent us from providing a more intensive exploration of this subject. In particular, we definitely need to enhance the teaching of MMF with hands-on experiments in modal dispersion. Our department is working on this problem. For example, we've introduced optical communications as a new area of concentration (track) in our bachelor of telecommunications technology program. This track, which includes three specialized courses in fiber-optic communications, will allow us to devote more time to the study of each specific subject, including MMF. This development will certainly result in the introduction of new laboratory exercises and will allow us to cover this subject in depth.

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BIOGRAPHY

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