Halit Eren. "Optical Loss."

Optical Loss

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59.1 Basic Concepts

Different properties of optics are used in many instrumentation and measurement devices. Applications vary from photographic imaging to high-speed data transmission via fibers. Once the light is generated and propagated from a source, it can be expanded, condensed, collimated, reflected, polarized, filtered, diffused, absorbed, refracted, scattered, etc. for manipulation and processing. Some of these manipulations are done to serve a particular purpose, and some results from physical characteristics of the light and optical properties of the media. In many applications, the intensity of light at the beginning will not be the same at the end due propagation characteristics and losses. It is important to point out that the word "light" is usually taken as radiation in the range of from about 380 nm to about 800 nm. This understanding limits important applications to those in the near-infrared and ultraviolet regions of the spectrum. In here, when the term "light" is used, the IR and UV portions of the spectrum are not left out.

The interpretation and treatment of "optical loss" is different for each individual instrumentation and measurement activity. It entirely depends on the purpose and method of measurements. For example, scattering of the light (radiation) from clouds is a useful property for determining atmospheric characteristics, whereas scattering of light in optical fibers may not be desirable due to resulting losses in power and decrease in efficiency. While many instrumentation systems (e.g., imaging) make use of scattering, absorption, refraction, and reflection as useful properties, in others these are considered to be mere losses that cause undesirable attenuations. In recent years, fiber optics has attracted considerable attention, and most of the following discussion on optical loss is centered on this subject. Likewise, this chapter concentrates on optical losses in fiber optics to clearly demonstrate the fundamental principles. Nevertheless, it is important to recognize that the same as losses in fiber optics may not be regarded as losses in other applications. It will be shown here that losses in fiber optics have useful properties in determining the optical fiber characteristics.

Theoretically, light propagation in fibers can be treated in a number of ways. For example, in treating propagation by modes, the fibers are viewed as optical waveguides, whereas treatment by rays is an approximate description of fibers with diameters much greater than the wavelength. In this chapter, both approaches will be used as appropriate.

An optical fiber is a circular dielectric glass (some polymers are also used) waveguide that can efficiently transport optical energy, and the information in the energy, usually by using the principle of total internal reflection. In some cases, it consists of a central glass core surrounded by a concentric cladding material with a slightly lower (≈1%) refractive index. Since the core has higher index of refraction than the cladding, light is confined to the core if the angular condition of total internal reflection is met. Attenuation of the light begins the moment light enters the fiber. The acceptance and transmission of light depends greatly on the angle at which the light enters the fiber. The angle must be less than the *critical acceptance angle* of the particular fiber being used, as shown in Figure 59.1.

There are three basic types of fibers: single-mode step-index, multimode graded index, and multimode step index, as shown in Figures 2a, 2b, and 2c, respectively. The characteristics of optical losses in these three types of fibers vary slightly due to differences in construction and the nature of propagation of light. For example, in the case of multimode step-index fibers, light striking the core–cladding junction at an angle greater than the angle of internal reflection passes through and becomes absorbed by the opaque jacket. This represents a significant source of attenuation, limiting the injection efficiency at the transmitting end.

Single-mode fibers, Figure 59.2a, are used in transmitting broadband signals over large distances. Their attenuation is generally very small, and their transmission band is large. Owing to material properties, low attenuations can be expected for wavelengths around 1.3 to 1.6 μm. Additional attenuation arises from splices and fiber bending.

Multimode graded-index fibers have medium size cores (50 to 100 μm) and refractive indices that decrease radially outward. The two optical materials with different refractive indices are mixed together in such a way that the index of refraction decreases smoothly with distance from the fiber axis. The graded index causes the light to gradually bend back and forth across the axis in sinusoidal manner when very small injection angles are used. This greatly reduces the light losses from the fiber and results in relatively better bandwidth and efficiency. The graded-index fibers also allow the use of simpler splicing techniques.

Good-quality fibers are typically made of pure silica with index modifying dopants such as GeO_2. While bandwidth is the primary consideration in the use of fiber optics in communication applications, light attenuation characteristics are equally important. The overall quality of a fiber optic light guide is determined by its light transmissivity, defined as the ratio of the output light to that put into the fiber.

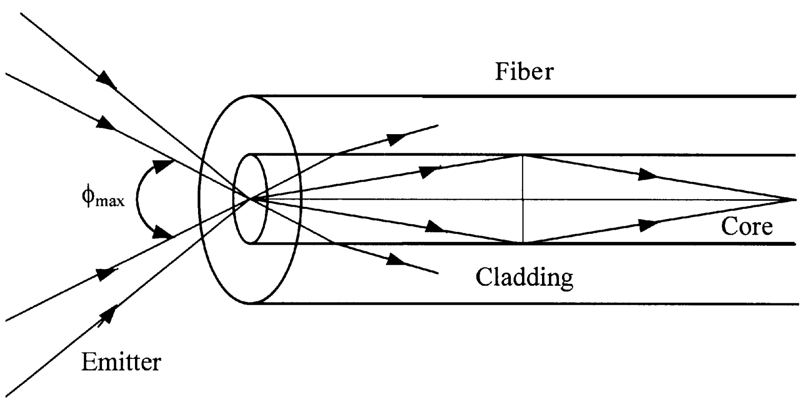

FIGURE 59.1 An optical fiber is a circular dielectric glass waveguide that can efficiently transport optical energy. It consist of a central glass core surrounded by a concentric cladding material. An important requirement for the connection of a light source is that a sufficient amount of useful light must be coupled into the fiber. The core has a higher index of refraction than the cladding; therefore, light is confined to the core only if the angular condition of total internal reflection is met. The acceptance and transmission of light depend greatly on the angle at which the light rays enter the fiber, and it must be less than the *critical acceptance angle* of a particular fiber.

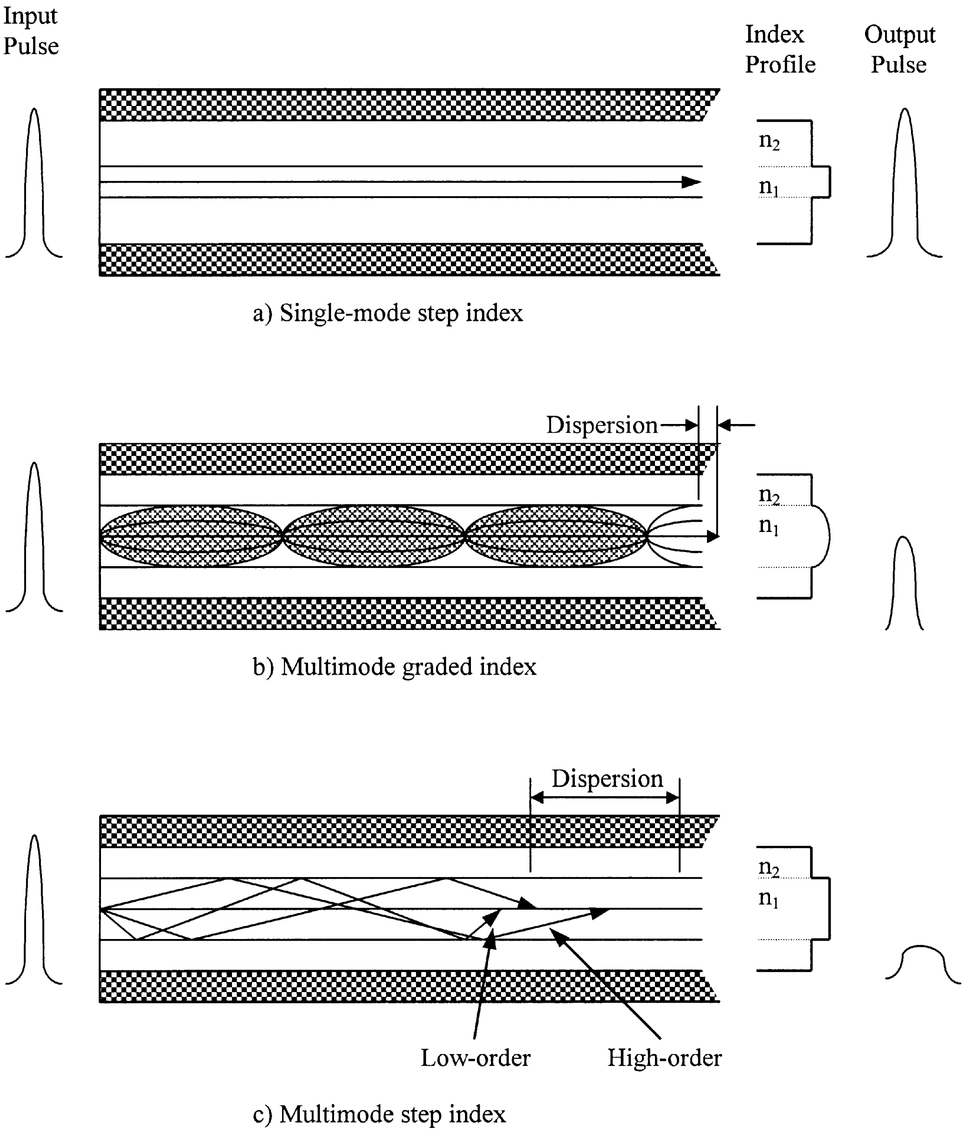

FIGURE 59.2 Three basic types of fibers. (a) Single-mode step-index fibers, used in transmitting broadband signals over large distances, (b) multimode graded index, obtained by mixing two optical materials with different refractive indices together in such a way that the index of refraction decreases smoothly with distance from the fiber axis, and (c) multimode step index fibers, in which the refractive index changes between fiber and cladding, and rays striking the core-cladding junction reflect back in the glass.

LEDs are the primary light source used in fiber-optic links for bit rates up to 200 Mb/s and distances up to 2 km. For higher bit rates and longer distances, diode lasers are preferred. LEDs used in fiber-optic applications operate at three narrowly defined wavelength bands 650, 820 to 870, and 1300 nm. The choice of wavelength is also determined by the transmission characteristics of optical fibers.

59.2 Optical Loss Mechanisms in Optical Fibers

There are two basic categories of sources of light loss in the fiber optic systems: extrinsic and intrinsic losses.

Extrinsic Fiber Losses

These losses are specific to geometry and handling of the fibers and are not functions of the fiber material itself. There are three basic types:

bending losses
launching losses
connector losses

Bending Losses

Bending losses are the result of distortion of the fiber from the ideal straight-line configuration. While the light is traveling inside the fiber, part of the wavefront on the outside of the bend must travel faster than the part of the smaller inner radius of the bend. Since this is not possible, a portion of the wave must be radiated away. Losses are greater for bends with smaller radii, particularly for kinks or microbends in a fiber.

An important cause of attenuation is due to microbending of the fiber. Microbending is due to irregularly distributed undulations in the fiber with radii of curvature of a few millimeters and deviations from the mean line of a few micrometers, as exemplified in Figure 59.3. Microbends arise from mechanical tensile forces by which the fiber is pressed against a rough surface. Although the effect of variations in diameter can be discussed at length by waveguide theory, here it will be sufficient to say that those components of the light that are traveling in the fiber near its acceptance limit cross outside this boundary and are lost from the fiber. These losses may be avoided by careful cable constructions, avoiding excessive mechanical forces, and controlling the temperature variations of the cable. This is achieved by a loose encasing of the fiber in a plastic sheath or by covering the fiber with soft flexible material, as shown in Figure 59.4.

Launching Losses

The term *launching loss* refers to an optical fiber not being able to propagate all the incoming light rays from an optical source. These occur during the process of coupling light into the fiber (e.g., losses at the interface stages). Rays launched outside the angle of acceptance excite only dissipative radiation modes in the fiber. In general, elaborate techniques have been developed to realize efficient coupling between the light source and the fiber, mainly achieved by means of condensers and focusing lenses. The focused input beam of light needs to be carefully matched by fiber parameters for good coupling.

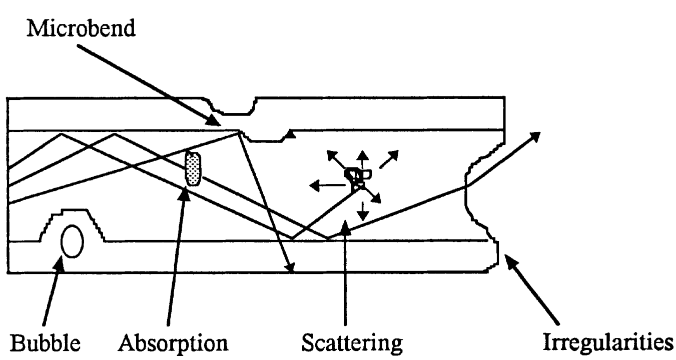

FIGURE 59.3 An important cause of attenuation is due to microbending of the fiber. This is due to irregularly distributed undulations in the fiber and from mechanical tensile forces when the fiber is pressed against a rough surface. Absorption losses are caused by the presence of impurities such as traces of metal ions (e.g., Cu^{2+}, Fe^{3+}) and hydroxyl (OH^-) ions. Despite careful manufacturing techniques, fibers can be inhomogeneous, having disordered, amorphous structures. Power losses due to scattering are caused by such imperfections in the core material and irregularities between the junction and cladding.

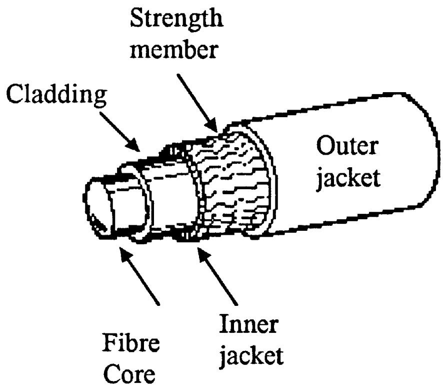

FIGURE 59.4 Some fiber losses can be avoided by careful cable construction, eliminating excessive mechanical forces, and controlling the temperature variations of the cable assembly. This is achieved by a loose encasing of the fiber in a plastic sheath or by covering the fiber with soft flexible materials. Most optical fibers constructed for communication purposes have inner and outer jackets for protection and strength.

Equally, once the light is transmitted through the fiber, output fiber characteristics must also match the output target characteristics to be able to couple the largest proportion of the transmitted light. This can be done by a suitable focusing lens arrangements in the output end.

There are also initial face (Fresnel) losses due to reflections at the entrance aperture. The Fresnel losses are greater if the fiber/source is air coupled. Hence, most optical couplings to a fiber utilize index matching materials, thus reducing coupling loss substantially.

Connector Losses

Connector losses are associated with the coupling of the output of one fiber with the input of another fiber, or couplings with detectors or other components. The significant losses may arise in fiber connectors and splices of the cores of the joined fibers having unequal diameters or misaligned centers, or if their axes are tilted. Mismatching of fiber diameters causes losses that can be approximated by $-10 \log(d/D)$. There are other connection losses such as offsets or tilts or air gaps between fibers, and poor surface finishes. Some of these are illustrated in Figure 59.5.

To take full advantage of fiber characteristics in transmission systems of very low intrinsic attenuation, the contribution of losses from other sources must also remain very small. The attenuation $a_s(d)$ due to coupling efficiency may be expressed as:

$$a_s(d) = -10 \text{ dB} \log\eta(d) \tag{59.1}$$

where $\eta(d)$ is the coupling coefficient.

In general, the positions and shapes of the fiber cores are controlled to tight manufacturing tolerances. Fibers having attenuations greater that 1 dB/km are rarely used in communication networks. Nevertheless, the attenuation of badly matched fibers may exceed 1 dB/km per connector or splice if they are badly handled during installation stages. A good coupling efficiency requires precise positioning of the fibers to center the cores. The simplest way to avoid connector losses is by splicing the two ends of the fibers permanently, either by gluing of by fusing at high temperatures.

Losses in gaps can be viewed as a type of Fresnel loss because existing air space introduces two media interfaces and their associated Fresnel reflection losses. In this case, there are two major losses to be considered. The first loss takes place in the inner surface of the transmitting fiber, and the second loss occurs due to reflections from the surface of the second fiber. One way of eliminating these losses is by introducing a coupler that matches the optical impedances of the two materials. This arrangement results in matched reflection coefficients, which is analogous to matching of impedances.

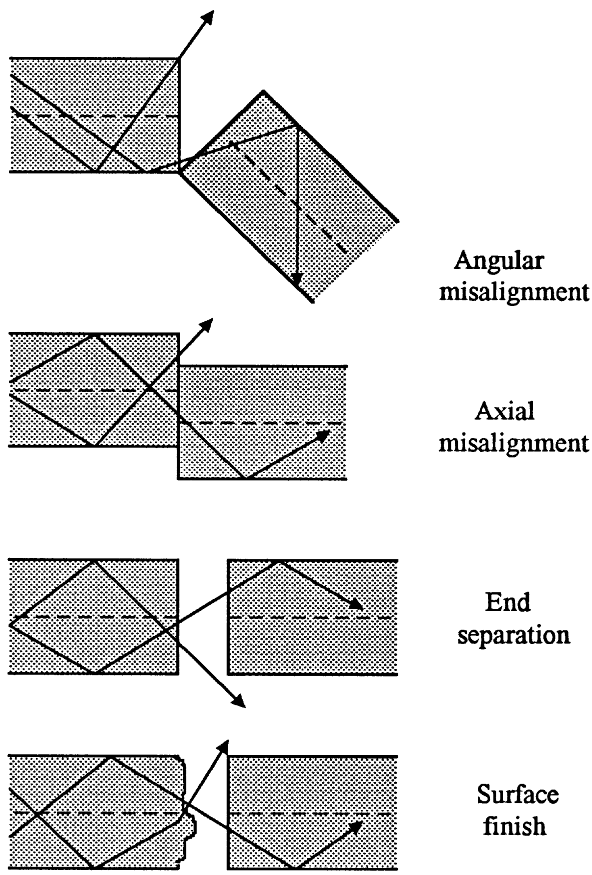

FIGURE 59.5 Connector losses are associated with the coupling of the output of one fiber with the input of another fiber or other components. Significant losses may arise in fiber connectors and splices of the cores of the joined fibers having unequal diameters, misaligned centers, tilted axes, and air gaps between fibers. In practical applications, fibers are permanently spliced by gluing or fusing at high temperatures.

Intrinsic Fiber Losses

Intrinsic fiber losses are those associated with the fiber optic material itself, and the total loss is proportional to length *L*. Once inside the fiber, light is attenuated primarily because of absorption and scattering; therefore, these are the primary causes of the losses.

Absorption Losses

As in the case of most transmissive systems, light loss through absorption in an optical fiber tends to be an exponential function of length. Absorption loss is caused by the presence of impurities such as traces of metal ions (e.g., Cu^{2+}, Fe^{3+}) and hydroxyl (OH^-) ions. Optical power is absorbed in the excitation of molecular vibrations of such impurities in the glass, as illustrated in Figure 59.3. One characteristic of absorption is that it occurs only in the vicinity of definite wavelengths corresponding to the natural oscillation frequencies or their harmonics of the particular material. In modern fibers, absorption losses are almost entirely due to OH^{-1} ions. The fundamental vibration mode of these ions corresponds to λ = 2.73 μm and the harmonics at 1.37 and 0.95 μm. It is possible to employ dehydration techniques during manufacturing to reduce presence of OH^{-1} ions.

Unlike scattering losses, which are relatively wideband effects, absorption losses due to each type of impurity act like a band-suppression filter, showing peak absorption at well defined wavelengths.

Scattering Losses

Despite the careful manufacturing techniques, most fibers are inhomogeneous that have disordered, amorphous structures. Power losses due to scattering are caused by such imperfections in the core material and irregularities between the junction and cladding as shown in Figure 59.3.

Inhomogeneities can be either structural or compositional in nature. In structural inhomogeneities, the basic molecular structure has random components, whereas, in compositional inhomogeneity, the chemical composition of the material varies. The net effect from either inhomogeneity is a fluctuation in the refractive index. As a rule of thumb, if the scale of these fluctuations is on the order of $\lambda/10$ or less, each irregularity acts as a scattering center. This is a form of Rayleigh scattering and is characterized by an effective absorption coefficient that is proportional to λ^{-4}. Rayleigh scattering can be caused by the existence of tiny dielectric inconsistencies in the glass. Because these perturbations are small with respect to the waves being propagated, light striking a Rayleigh imperfection scatters in all directions. Scattering losses are less at longer wavelengths, where the majority of the transmission losses are due to absorption from impurities such as ions. Rayleigh scattering losses are not localized, and they follow a distribution law throughout the fiber. However, they can be minimized by having low thermodynamic density fluctuations.

A small part of the scattered light may scatter backward, propagating in the opposite direction. This backscattering has important characteristics and may be used for measuring fiber properties. Usually, the inhomogeneities in the glass are smaller than the wavelength λ of the light. The scattering losses in glass fibers approximately follow the Raleigh scattering law; that is, they are very high for small wavelengths and decrease with increasing wavelength.

In general, optical losses in the glass cause the optical power in a fiber to fall off exponentially with the length L of the fiber,

$$P(L) = P(0)\ 10^{(-\alpha L/10\text{dB})} \tag{59.2}$$

where $P(0)$ = optical power that couples to the fiber, $P(L)$ = power remaining after length L, and α is the attenuation coefficient indicating the rate of loss of optical power in dB/km.

The product αL is called the *attenuation of the fiber.* An attenuation of 10 dB means that the optical power $P(L)$ at the end of the fiber is only 10% of the initial power $P(0)$. A 3-dB attenuation gives 50%, and 1 dB is about 80%.

A typical attenuation coefficient α against wavelength λ is shown in Figure 59.6 for common low-loss fused silica fiber. The optical losses for wavelengths below 1 µm are mainly due to Rayleigh scattering. At larger wavelengths absorption losses are important, notably at 1.4 µm through absorption by OH^{-1} ions. Above 1.6 µm, absorption due to impurities becomes dominant. Because of attenuations, only limited wavelength ranges are appropriate for optical data transmission.

Although intrinsic fiber losses can be associated with the core index n_f, the core index has an important role in determining the propagation time delay of optical signals. The propagation time delay t_p may be expressed by

$$t_p = n_f\ L/c \tag{59.3}$$

where c = velocity of light in the fiber, and L = fiber length.

Another type of loss in optical fibers occurs due to the propagation of light at different angles. Light propagating at shallow angles is called *low-order mode*, and light propagating at larger angles is called *high-order mode.* For a given length of fiber, the high-order modes reflect more often and cover longer distances than the low-order modes. Therefore, high-order modes suffer more losses, thus causing modal dispersions. The modal dispersion is one of the primary cause of rise time degradation for increasing fiber wavelengths. In addition, propagation time varies with index of refraction, so different wavelength components of the source spectrum have different travel times, thus causing *chromatic dispersion*.

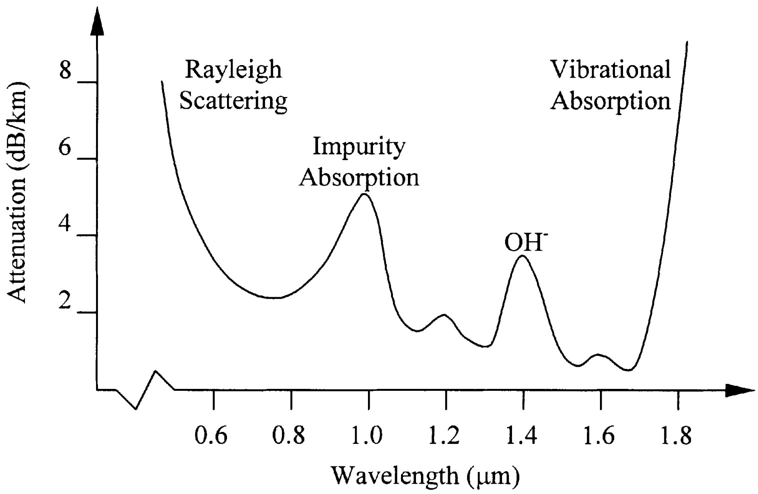

FIGURE 59.6 Attenuation characteristics of a typical optical fiber. The attenuation coefficient α varies with wavelength for all low-loss fused silica fibers due to Rayleigh scattering and impurity absorptions. The optical losses for wavelengths below 1 μm are mainly due to scattering. At greater wavelengths, absorption losses are important, notably at 1.4 μm through absorption by OH^{-1} ions. Above 1.6 μm absorption due to impurities becomes dominant.

59.3 Optical Time Domain Reflectometry Method

Optical time domain reflectometers (OTDRs) are used mainly for link testing. In this instrument, optical power is launched into the fiber, and the reflected power associated with Rayleigh scattering and other backscattering mechanisms are measured in the sending end, as shown in Figure 59.7. Manufacturers usually provide the instrument with customized analysis software and optical modules to be integrated into a computer. OTDR complements attenuation measurements by measuring the backscattering. This permits not only the attenuation of the complete fiber to be measured, but also different attenuation coefficients of fiber segments, as well as optical losses in connectors and splices. Furthermore, it indicates the location of such optical losses as well as the length of the fiber.

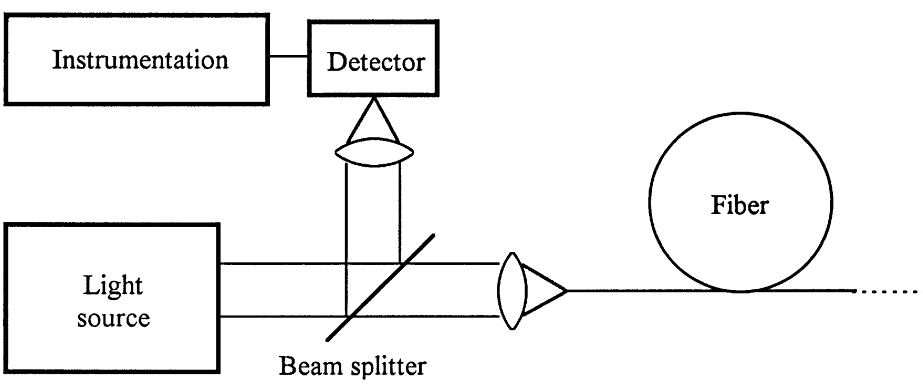

FIGURE 59.7 Optical time domain reflectometers (OTDRs) are used in link tests. The optical power is launched into the fiber, and the reflected power associated with Rayleigh scattering is measured from the same sending end. OTDRs usually are offered with customized analysis software and optical modules to be integrated into a computer. OTDR complements attenuation measurements by measuring the backscattering. This permits not only the attenuation of the complete fiber to be measured but also different attenuation coefficients of fiber segments, as well as optical losses in connectors and splices.

In OTDRs, as Figure 59.8 illustrates in block diagram form, short, intense laser pulses with duration Δt = 10 to 100 ns at peak power $M_{ax}(0)$ are coupled to the fiber. Backscattering echoes are detected from different regions of the fiber. In traversing the fiber, the power of these impulses decreases exponentially with the length of the fiber, predominantly due to scattering. A small portion of the scattered light reverses its direction and returns to the transmitter. The returned signal is uncoupled from the fiber by means of a beam splitter, to be processed further. The time history of the returned signals can be expressed as:

$$P_R(t) = K_R \, M_{ax}(0) \, \Delta t \, 10^{(-2\alpha L/10 \text{ dB})} \tag{59.4}$$

where K_R = the backscattering factor of the fiber.

The backscattering factor depends on scattering and numerical aperture. It is small, such that P_R(t) is reduced as compared to $M_{ax}(0)$, typically by a factor of 50 to 60 dB. Despite this reduction, it is possible to measure the characteristics of fibers that are several kilometers long. In many cases, light pulses with high energy contents are used, along with sensitive receivers based on avalanche photodiodes.

The evolution with time of the backscattering signal P_R(t) is given in Figure 59.9. If the attenuation coefficient and backscattering factors were constant throughout the length of the fiber, a curve that decreases exponentially from left to right would result. However, some power is reflected back from the end of the fiber because of some discontinuity. This appears as a sharp pulse at the right-hand side of the curve. In practical fibers, local optical losses as well as continuous losses occur due to imperfect connectors and splices. From the location and height of the steps, the position and magnitude of the local losses can easily be identified. The length of the fiber can also be obtained from timing of this pulse.

Other disturbances in the propagation of the light are also revealed in the backscattering signal. For example, variations in the attenuation coefficient of spliced fiber segments can be seen as slope changes in the P_R(t) curve. In such cases, all information of importance can be drawn from the backscattering signal to enable the calculation of the attenuation and the local attenuation coefficients. A practical advantage of this method is that in measurements only one end of the fiber needs to be accessible; therefore, measurements can be done on optical cables that have already been laid.

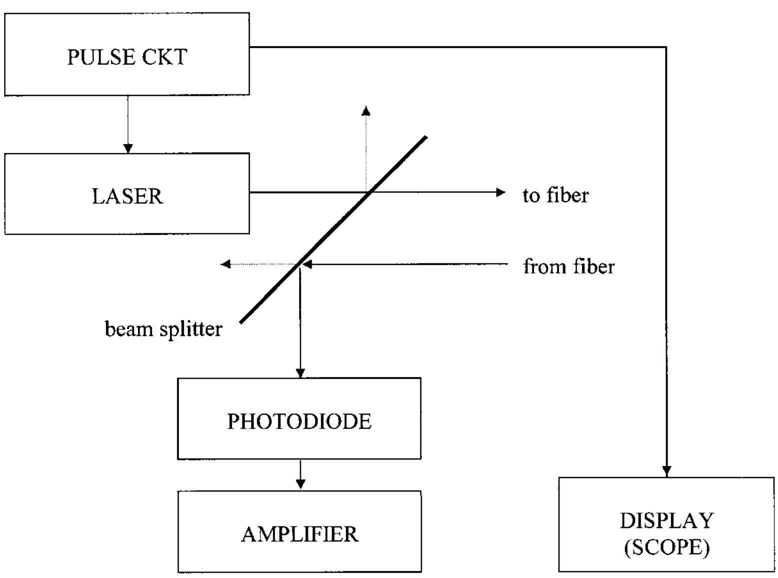

FIGURE 59.8 OTDRs usually come with a laser source, with modules that allow wavelength selection. The short, intense laser pulses with high peak power are coupled to the fiber. Backscattering echoes are detected from different regions of the fiber. The returned signal is uncoupled from the fiber by means of a beam splitter, to be processed further for analysis.

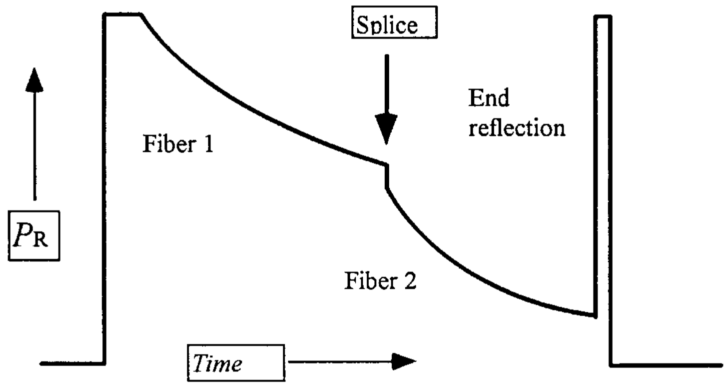

FIGURE 59.9 A typical example of the evolution of a backscattering signal in time. An exponential curve that decreases from left to right is obtained due to attenuation coefficients and backscattering factors. Some power reflects back from the end of the fiber and other discontinuities such as glass-air boundaries, appearing as sharp pulses. From the location and height of these returned sharp pulses, the positions and magnitudes of the local losses can easily be identified. The change of slope of curve also indicates the change in attenuation coefficient if different fibers are used.

59.4 Standard Field Fiber Optic Attenuation Test

In practical applications of optical fibers, it is necessary to have quantitative knowledge on the whole range of properties. Most important properties are length, attenuation, and bandwidth of the fibers, along with external diameter, core diameter, numerical aperture, and refractive index profile. The actual performance of installed links may be different from the desired performance. Therefore, it is important that both individual components and the entire assembled system undergo testing to verify compliance with the required operations. Additional testing may be conducted over the life of the system to ensure continued functional operation over long periods of time.

There are two basic standard fiber optic attenuation tests: the component acceptance test and the link test. The component acceptance test is performed prior to installation to verify the power and performance acceptance levels of each fiber. The acceptance testing of a functional module begins with power testing of the transmitter. The testing is done by attaching the module set into a reference link and verifying the data rates and bit error rates taken at the other end of the fiber, as shown in Figure 59.10.

Fiber acceptance testing also requires power testing, which can be done by launching a known power from a reference source, as explained in the OTDR section. The functional testing verifies power budget of coupling attenuation effects as well as bandwidth for the fiber. The attenuation and power transmission depend on the mode distribution within the fiber. In short fibers, higher modes dominate, whereas in

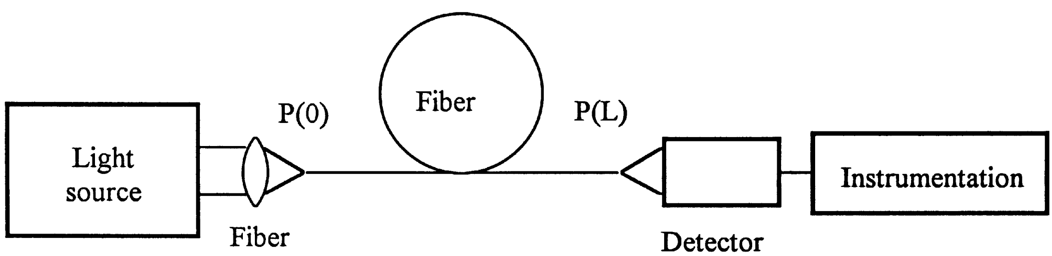

FIGURE 59.10 The measurements of transmission properties of laid optical fibers are obtained by end-to-end tests. The testing is done by attaching the module set into a reference link and verifying the data rates and bit error rates taken at the other end of the fiber.

long fibers, power is more concentrated in lower order modes. Mode stripping is often used by introducing small bends into the fiber to correlate the performance of tested fiber to actual in-service performance.

In addition to acceptance tests, fibers undergo other tests such as pull strength, breaking, humidity resistance, prolonged tension, and bend tests. Connectors, splitters, combiners, and fiber amplifiers need to be tested frequently to minimize power transmission losses.

In almost all fiber optics, low noise and very sensitive photodetectors are used in measurements. Semiconductor photodiodes made from silicon are suitable for measurements with wavelengths below 1 µm. For larger wavelengths, other detectors are used, such as those made of germanium.

Semiconductor photodiodes work via the internal photoelectric effect; that is, they absorb photons of energy $h\nu$ containing the incoming light beam power P and emit a number of electrons proportional to the number of photons, creating a current:

$$i_p = P\eta e/h\nu \tag{59.5}$$

where h = Planck's constant, ν = frequency of the absorbed light ($\nu = c/\lambda$), η = a constant of proportionality or quantum efficiency ($\eta < 1$), and e = the charge of an electron.

Photodetectors are used to measure the attenuation in fibers by measuring the optical power in the input $P(0)$ and power $P(L)$ at the end of the of the fiber. From Equation 59.1, the attenuation of the fiber can be calculated as:

$$a_0 = \alpha L = -10 \log P(L)/P(0) \tag{59.6}$$

When photodetectors are used Equation 59.4 can be written as

$$a_0 = -10 \log i_p(L)/i_p(0) \tag{59.7}$$

It is worth noting that optical power is proportional to current i_p, not to i_p^2.

Light-emitting diodes (LEDs) or incandescent halogen lamps are suitable for use as light sources for attenuation measurements. If LEDs are used, several interchangeable ones are needed, suitable to different wavelengths to make measurements. On the other hand, halogen lamps yield a wide spectrum of radiation, from which light of various wavelengths can be filtered with a monochromator that uses optical filters, prisms, or diffraction gratings. With an arrangement of this kind, the attenuation of the fiber can be measured as a function of the wavelength of the light.

To measure small optical powers precisely for the purpose of determining attenuation, the photodetector is usually connected to a selective amplifier, and the light source is modulated at low frequency (e.g., 400 Hz) using a rotating disk called a *chopper*. The selective amplifier amplifies only the similarly modulated components of the photocurrent, so that detector noise and the influence of background light are suppressed. For this purpose, frequency-selective level meters or lock-in amplifiers are often used. In both cases, the frequency and phase of the modulation are fed back in the form of reference voltage.

59.5 Out-of-Plane Scattering and Polarization Methods

The art of scatter measurements has long been evolved to established forms within the optics industry. Scatter methods provide extremely sensitive measurements in many diverse applications. There are two basic instruments developed for this purpose; the scatterometer and the polarimeter.

The basic setup for a scatterometer is given in Figure 59.11. Measured scatter is a good indicator of surface quality as well as discrete defects. However, the scattered signals are generally small compared to the specular beams, and they can vary by several orders of magnitude in just a few degrees. Therefore, scatter measurements need sophisticated instrumentation and the signal processing is more complex than many other optical techniques. Usually, for successful applications, the system specifications and measurements must be given in terms of accepted, well defined quantities. Scatter methods are used

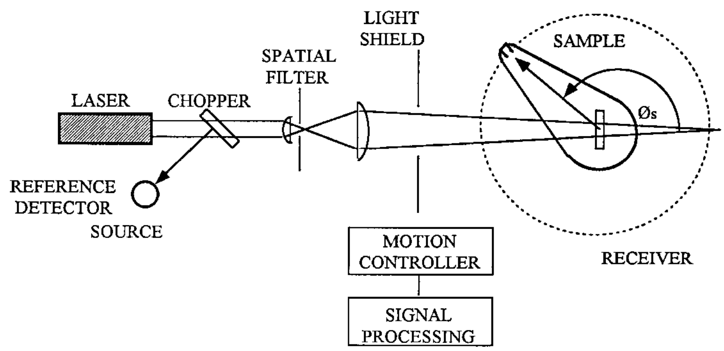

FIGURE 59.11 A typical scatterometer. In this particular type, the source is fixed in position, and the sample is rotated to the required incident angle. The receiver is rotated about the sample in the plane of incidence. In other types, the source and receiver may be fixed, and the sample is rotated so that the scatter pattern moves past the receiver. Scatterometers are offered with full supporting software.

routinely as a quality check on optical components in fiber-optic applications. Conversion of surface scatter data to other required formats, such as surface roughness, is common practice. Out-of-plane measurements and polarization-sensitive measurements are areas currently experiencing rapid advancements.

Another instrument in common use is the polarimeter, which senses the polarization of scattered light. The scattering characteristics of a sample are generally described by its bidirectional reflectance distribution function. The reflectance distribution function is the ratio of scattered flux in a particular direction to the flux of an incident beam. The scattered light is often a sensitive indicator of surface conditions. A small amount of surface roughness may reduce the specular power by less than 1% while increasing the scattered power by orders of magnitude. The retardance, attenuation, and depolarization of scattered light similarly provide sensitive indicators of conditions, such as uniformity of refractive index, orientation of surface defects, texture, strain, subsurface damage, coating microstructure, and the degree of multiscattering. Among many other methods, the use of prisms helps polarization and depolarization of the scattered light.

Instrument manufacturers are listed in Table 59.1, along with contact information.

TABLE 59.1 List of Manufacturers

AXSYS Communications P.O. Box 571 Danielson, CT 06239-0571 Tel: (203) 774-4102 Fax: (203) 774-4783	**Chiu Technical Corp.** 252 Indian Head Rd. Kingspark, NY 11754 Tel: (516) 544-0606 Fax: (516) 544-0809
Cuda Products Corp. 6000-T Power Ave. Jacksonville, FL 32217-2279 Tel: (904) 737-7611 Fax: (904) 733-4832	**Fiberoptic Technology Inc.** 13 Fiber Rd. Pomfret, CT 06258 Tel: (800) 433-5248, (203) 928-0443 Fax: (800) 543-2558, (203) 928-7664
Fiber Options 80-T Orville Dr. Bohemia, NY 11716-2533 Tel: (800) 739-9105, (516) 567-8320 Fax: (516) 567-8322	**INCOM Inc.** P.O. Drawer G. Southbridge, MA 01550-0528 Tel: (508) 765-9151 Fax: (508) 765-0041
PHILTEC Inc. P.O. Box 359 Arnold, MD 21012 Tel: (410) 757-4404 Fax: (410) 757-8138	**VICON Fiber Optics Corp.** 90 Secor Lane Pelham Manor, NY 10803 Tel: (800) 828-2071, (914) 738-5006 Fax: (914) 738-6920

Additional Information

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