CHAPTER

17

Fiber-Optic Measurements

About This Chapter

Fiber-optic technology has its own distinct set of measurements, based largely on a mixture of optical and electronic techniques. This chapter covers the important optical aspects of fiber-optic measurements, assuming you know something about electronics. It covers measurement units, the quantities measured, and the types of measurements performed, pointing out differences between optical and electronic measurements.

The emphasis here is on basic optical concepts that you need to know when working with fiber optics. The next chapter covers fiber-optic test equipment, along with its use in troubleshooting fiber-optic systems.

Basics of Optical Power Measurement

Most important fiber-optic measurements involve light, in the same way that important electronic measurements involve electric fields and currents. There are some exceptions, such as the length and diameter of optical fibers and cables, the sizes of other components, and the electrical characteristics of transmitter and receiver components. Because this is a book about fiber optics, I will mention such measurements only in passing. However, I will talk about measuring some things other than light, because you cannot quantify the properties of optical fibers if you consider only light. For example, to measure the dispersion of light pulses traveling through an optical fiber, you must observe how light intensity varies as a function of time, which requires measuring time as well as light.

When you're working with light, you need to know what can be measured. The most obvious quantity is optical power, which like electrical voltage is a fundamental measuring stick. However, power alone is rarely enough; it usually must be measured as a function

Fiber-optic measurements involve light and other quantities, such as the variation of light with time.

Specialized terminology makes fine distinctions about quantities related to optical power.

of other things, such as time, position, and wavelength. Wavelength itself is important because optical properties of optical components, materials, light sources, and detectors all depend on wavelength. Other quantities that are sometimes important are the phase and polarization of the light wave. You need to learn a little more about these concepts before getting into more detail on measurement types and procedures.

Optical Power and Energy

People have an intuitive feeling for the idea of optical power (measured in watts) as the intensity of light. However, a closer look shows that optical power and light intensity are rather complex quantities and that you need to be careful what you talk about. Table 17.1 lists the most important quantities, which are described in more detail later.

Each photon or quantum of light carries a characteristic *energy*, as you learned in Chapter 2. Energy is often denoted by E, but the symbol Q is often used in optics. The amount is a function of the wavelength or frequency of the electromagnetic wave. *Photon energy* is easiest to express as the frequency of the wave (ν) times Planck's constant h, which equals 6.63×10^{-34} joule-second, or 4.14×10^{-15} electron-volt-second.

$$\text{Energy} = h\nu$$

When working in wavelength units, the formula for photon energy (in joules) is

$$\text{Energy } (J) = \frac{hc}{\lambda}$$

where c is the speed of light (approximately 300,000 km/s) and λ the wavelength in meters. If the wavelength is expressed in micrometers, the formula for photon energy (in electron volts) becomes

$$\text{Energy (eV)} = \frac{1.2406}{\lambda(\text{in } \mu\text{m})}$$

Table 17.1 Measurable quantities related to optical power

Quantity and Symbol	Meaning	Units
Energy (Q or E)	Amount of light energy	joules
Optical power (P or ϕ) (or radiant flux)	Flow of light energy past a point at a particular time (dQ/dt)	watts
Intensity (I)	Power per unit solid angle	watts per steradian
Irradiance (E)	Power incident per unit area	W/cm^2
Radiance (L)	Power per unit solid angle per unit projected area	W/steradian-m^2
Average power	Power averaged over time	watts
Peak power	Peak power in a pulse	watts

Photon energy is the energy carried by a single photon. Normally a pulse of light contains many photons, and the total pulse energy carried by the pulse is the sum of all the photon energies. You can think of energy as the sum of the energies of all the photons that arrive at a destination. However, only knowing the total energy does not tell you if the energy arrived in a single pulse lasting a tiny fraction of a second, or in a slow but steady trickle that took all day.

Power (P or ϕ) measures the rate of energy transfer per unit time. You can think of it as the rate at which photons (or, equivalently, electromagnetic waves) carry energy through the system or arrive at their destination. The rate of energy transfer can vary with time, so power is a function of time. Mathematically, power P is expressed as a rate of change or derivative with respect to energy (Q):

$$\text{Power} = \frac{d(\text{energy})}{d(\text{time})}$$

or

$$P = \frac{dQ}{dt}$$

Sometimes called *radiant flux*, optical power is measured in watts. One *watt* is defined as the flow of one joule of energy per second. Watts are units used to measure the transfer rates of all types of energy, including electrical energy or heat. That is, a watt of light delivers the same amount of energy per second as a watt of electricity. (Note, however, that the power ratings of light bulbs in watts measure how much electrical power they use, not the amount of visible light they radiate, which is much lower.)

Optical and Electrical Power

Both optical and electrical power measure more fundamental quantities. For light and other types of electromagnetic radiation, the power is proportional to the square of the amplitude of the electromagnetic wave, shown as A in Figure 17.1, as well as to the number of photons received per second. The wave amplitude measures the strength of the electrical field in the wave.

Optical power is proportional to the square of the light wave amplitude.

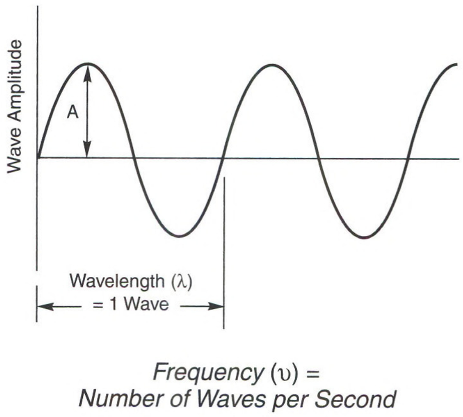


FIGURE 17.1
Properties of an electromagnetic wave.

Electrical power is usually given as the product of the voltage (V) times the current (I):

$$P = VI$$

or, power (in watts) = volts × amperes. The relationship can take other forms if you use Ohm's law, $V = IR$ (voltage = current × resistance):

$$\text{Power} = \frac{V^2}{R} = I^2R$$

Recall that voltage across a resistance is the strength of the electric field, and you can see that electrical power looks like optical power. It's easy to measure the voltage or current in electronics, but it's not easy to measure the amplitude of the electric field in light waves. Thus in electronics you may measure the voltage and current and multiply them to get power, but in optics you measure power directly.

A closer comparison of optical power and electronic power shows more about their differences and similarities. The energy carried by an electron depends on the voltage or electric field that accelerates it. Earlier, I mentioned the electron volt as a unit of energy. One *electron volt* is the energy an electron carries after it is accelerated through a potential of one volt. The total power is thus the number of electrons passing through a point times the voltage that accelerated them.

Energy per photon depends on the photon wavelength.

Each photon has a characteristic energy, which depends on its wavelength or frequency. If the light is at a steady level, the amplitude of the light wave measures the number of photons per unit time. Thus the total energy delivered by the light is the energy per photon times the number of photons (the wave amplitude).

This makes the two types of power look the same, and that stands to reason. Electrical power is the energy per unit time delivered by electrons, where the electron energy depends on the voltage that accelerated the electrons. Optical power is the energy per unit time delivered by photons, each of which has a fixed energy that depends on its wavelength. The total power measures the rate at which these photons are arriving.

There is a complication to this picture. Normally, a constant voltage accelerates all electrons to the same energy. However, all photons arriving at a given point do not have the same energy unless they all have the same wavelength. Lasers can deliver monochromatic light, with all photons having almost the same energy, but optical measurements were developed long before lasers, when there was no easy way to account for differences in photon energy. Instead of trying to count photons, optical power measurements usually average out the differences and give the results in watts.

Peak and Average Power

Power is an instantaneous measurement; it varies with time.

Power is an instantaneous measurement of the flux of energy at a given moment. This means that it can vary with time. In general, two types of power are measured in optical systems: *peak power* and *average power.*

The peak power is the highest power level reached in an optical pulse, as shown in Figure 17.2. This power may not be sustained long. In a fiber-optic system, this is the highest level reached while a signal is being transmitted.

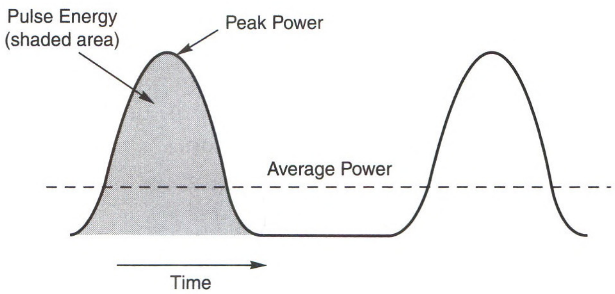


FIGURE 17.2
Peak and average power, and total pulse energy.

The average power measures the average power received over a comparatively long period, often a second. In a communication system, this is the average over many pulses and quiet intervals. For a digital fiber-optic system in which the transmitter is sending "on" pulses half the time (a 50% duty cycle), the average power is half the peak power because the power is either fully on or fully off. In the example of Figure 17.2, the average power is less than half the peak power because the power is lower than the peak during most of the pulse, and because no power is delivered between pulses.

Peak power is the highest level in an optical pulse; average power is the average over an interval.

The average power of an ideal digital transmitter also depends on the modulation scheme. Some modulation patterns and data streams do not keep the transmitter emitting light half the time.

In practice, fiber-optic measurements average power levels over many pulses to give average power rather than peak power. However, transmitter output may be specified as peak power, so it pays to check.

Pulse energy is another measurement that can be valuable. An example is trying to calculate how many photons arrive per pulse in high-speed systems, because that number drops with data rate. Suppose the average power in two signals is 10 μW. If one signal carries 2.5 Gbit/s and the second carries 10 Gbit/s, the pulses in the faster system will be only one-fourth the duration, and during that interval they will deliver only one-fourth the total energy carried by a pulse lasting four times as long. If you delve deeply into communication theory, you will find that the ultimate limits on communications often are stated as the minimum pulse energy needed to deliver a bit of information.

The ultimate limits on communications come from pulse energy.

Pulse energy measures the total energy received during a pulse, as shown in the shaded area in Figure 17.2. If the power is uniform during the length of the pulse, as in a series of square digital pulses, the pulse energy Q is the product of the power P times the time t:

$$Q = P \times t$$

If the instantaneous power varies over the length of the pulse, you need to integrate power over the pulse duration, which is mathematically expressed as:

$$Q = \int P(t)\,dt$$

As long as the power remains level during the pulse, multiplication works fine.

Optical Power Measurement Quirks

The definition of decibels looks different for power and voltage.

Before I go deeper into measuring various forms of optical power, I'll warn you about a few potentially confusing measurement quirks. In electrical measurements, the decibel power ratio is often defined in terms of voltage or current. These are in the form

$$\text{Power ratio (dB)} = 20 \log\left(\frac{V_1}{V_2}\right) = 20 \log\left(\frac{I_1}{I_2}\right)$$

where V and I are voltage and current, respectively.

Fiber-optic measurements usually give a different-looking equation in terms of powers P_1 and P_2:

$$\text{Power ratio (dB)} = 10 \log\left(\frac{P_1}{P_2}\right)$$

Why the different factor preceding the log of the power ratio? Because electrical power is proportional to the square of voltage or current. If you measure the ratio of voltage or current, you have to square it to get the power ratio, which is the same as multiplying the log of the ratio by 2. You don't have to do that if you measure power directly, either optically or electrically. Electrical measurements are usually in voltage or current, but optical measurements are in power, so it may seem that the difference is between optical and electrical. However, the real difference is between measuring power directly or indirectly. Both formulas are correct, but be careful to use the proper one.

Optical power can be measured in decibels relative to 1 mW (dBm) or 1 μW (dBμ).

A second potentially confusing point is measurement of optical power in some peculiar-seeming units. Normally, power is measured in watts or one of the metric subdivisions of the watt—milliwatts, microwatts, or nanowatts. Sometimes, however, it is convenient to measure power in decibels to simplify calculations of power level using attenuation measured in decibels. The decibel is a dimensionless ratio, so it can't measure power directly. However, power can be measured in decibels relative to a defined power level. In fiber optics, the usual choices are decibels relative to 1 mW (dBm) or to 1 μW (dBμ). Negative numbers mean powers below the reference level; positive numbers mean higher powers. Thus, +10 dBm means 10 mW, but −10 dBm means 0.1 mW. Zero means there is no difference from the reference level, so 0 dBm is 1 mW.

Such measurements come in very handy in describing system design. Suppose, for instance, that you start with a 1-mW source, lose 3 dB coupling its output into a fiber, lose another 10 dB in the fiber, and lose 1 dB in each of three connectors. You can calculate that simply by converting 1 mW to 0 dBm and subtracting the losses:

Initial power	0 dBm
Fiber coupling loss	−3 dB
Fiber loss	−10 dB
Connector loss	−3 dB
Final Power	−16 dB

Convert the -16 dBm back to power, and you find that the signal is 0.025 mW; however, that often isn't necessary because many specifications are given in dBm. This ease of calculation and comparison is a major virtue of the decibel-based units.

Types of Power Measurement

As Table 17.1 indicates, optical power measurements may include the distribution of power per unit area or angle. The main concern of fiber-optic measurements is with total optical power within a fiber, or reaching a detector; but the distribution of optical power can be vital for other applications, such as illuminating and imaging. You should understand the differences because the terminology can be confusing and it's important to understand what you're measuring.

LIGHT DETECTORS

Light detectors measure total power incident on their active (light-sensitive) areas—a value often given on data sheets. Fortunately, the light-carrying cores of most fibers are smaller than the active areas of most detectors. As long as the fiber is close enough to the detector, and the detector's active area is large enough, virtually all the light will reach the active region and generate an electrical output signal.

Light detectors measure total incident power.

The response of light detectors depends on wavelength. As you learned in Chapter 11, silicon detectors respond strongly at 650 and 850 nm but not at the 1300 to 1700 nm wavelengths used in long-distance systems. On the other hand, InGaAs detectors respond strongly at 1300 to 1700 nm but not to the shorter wavelengths. In addition, detector response is not perfectly uniform across their entire operating region. You have to consider the wavelength response of detectors to obtain accurate measurements.

Recall also that detectors cannot distinguish between different wavelengths within their operating regions. If eight WDM channels all reach the same detector, its electrical output will measure their total power, not the power of one channel.

In addition, individual detectors give linear response over only a limited range. Powers in fiber-optic systems can range from over 100 mW near powerful transmitters used to drive many terminals to below 1 μW at the receiver ends of other systems. Special detectors are needed for accurate measurements at the high end of the power range.

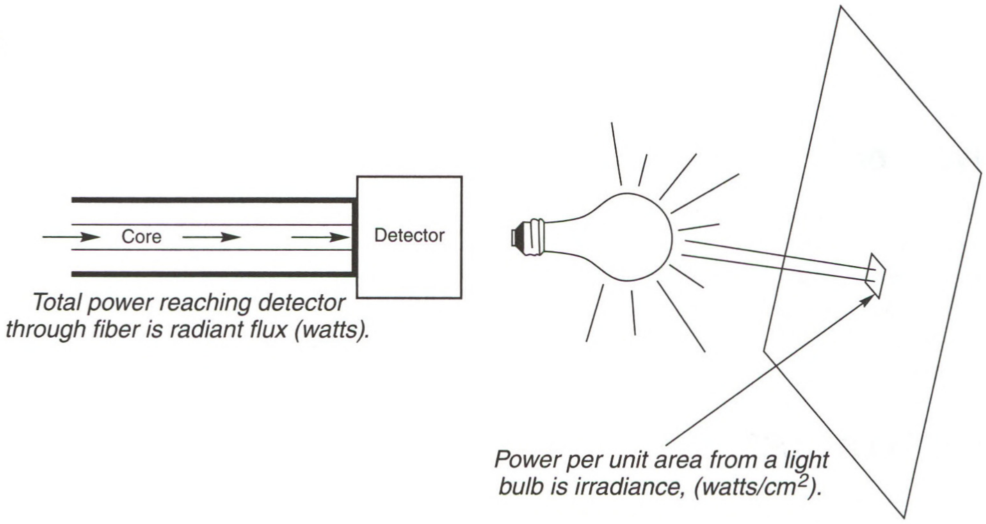
IRRADIANCE AND INTENSITY

Things are more complicated when measuring the distribution of optical power over a large area. For this case, another parameter becomes important, called *irradiance* (usually denoted E in optics), the power density per unit area (e.g., watts per square centimeter). Figure 17.3 compares the irradiance on a surface with the total power a detector collects from an optical fiber.

Irradiance (E) is power per unit area. Intensity (I) is power per unit solid angle.

You cannot assume irradiance is evenly distributed over the surface unless the light comes from a "point" source (i.e., one that is very distant or looks like a point), and the entire surface is at the same angle to the source. A book lying flat on the ground is uniformly illuminated by the sun, but the entire earth is not, because its surface is curved. Total power

FIGURE 17.3
Total power and irradiance.



(P) from a light source is the irradiance (E) collected over the entire illuminated area (A). For the simple example of the book in the sun, the total power is

$$P = E \times A$$

If the surface is not uniformly illuminated, the total power is integrated over the entire surface:

$$P = \int EA$$

The E for irradiance could be confused with the E more widely used for energy. Fortunately, irradiance is rarely used in fiber optics, and when the symbol E is used its meaning should be clear.

The term *intensity* (I) also has a specific meaning in light measurement—the power per unit solid angle (steradian), with the light source at the center of the solid angle. This measures how rapidly light is spreading out from the source.

Irradiance and intensity are often confused, and the power per unit area is often called intensity. This mistake is understandable because both units measure the distribution of power, one over a surface area, the other over a range of angles. The easiest way to tell is to look at the units; if someone measures "intensity" in watts per square centimeter, they're really talking about irradiance. There are fewer situations where power is measured per steradian.

Most fiber-optic measurements concern total power. However, irradiance and intensity may be important when measuring the concentration of power inside a fiber core, or when beams are directed through free space.

Radiometry measures all wavelengths. Photometry measures only visible light.

RADIOMETRY AND PHOTOMETRY

Optical measurements are divided into two broad categories, *radiometry* and *photometry*, which are sometimes confused. Photometry is limited to measuring light visible to the human eye, at wavelengths of 400 to 700 nm; invisible light doesn't count for photometry.

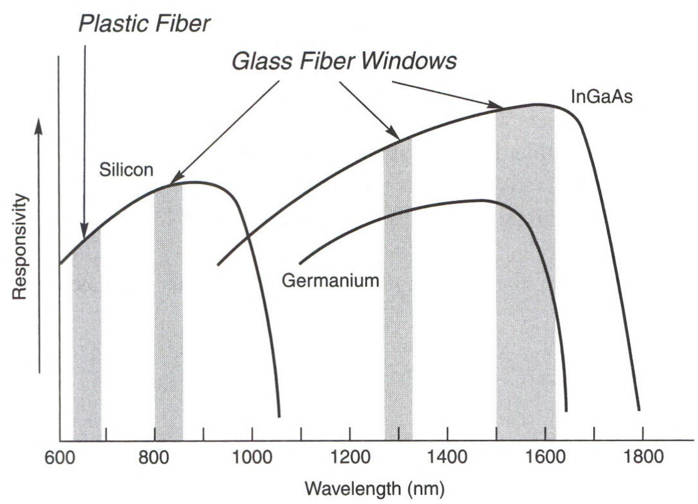


FIGURE 17.4
Detector response at different wavelengths.

Radiometry measures the total power of both visible and invisible light in watts, and it's radiometry that is used for fiber-optic measurements.

Photometry has its own measurement units, *lumens*, which are used to measure the visible light from bulbs. Lumens are not directly convertible to watts because lumens are weighted to account for how the eye's sensitivity varies with wavelength. Light at 550 nm, where the eye is most sensitive, counts more on a photometric scale than 450 or 650 nm, where the eye is less sensitive. Photometry ignores the infrared wavelengths used in fiber-optic communications. You should know what photometry is because many optical power meters are calibrated in both radiometric and photometric units, but you should use the radiometric units.

An ideal *radiometer* would be sensitive across the entire visible, ultraviolet, and infrared spectrum, but real detectors don't work that way. As you learned in Chapter 11, each type of detector responds to a different range of wavelengths, and is not equally sensitive across its entire range. Figure 17.4 shows the variations over the ranges of important detectors compared to the windows for fiber transmission. Power meters are calibrated to reflect detector response.

In practice, fiber-optic power meters are calibrated for measurements at the major fiber system windows, 650, 850, 1300, and 1550 nm. They may not be calibrated at intermediate wavelengths, and as you can see in Figure 17.4, at some wavelengths they may not even respond. All power meters measure average power. They respond much more slowly than signal speeds, so they can't track instantaneous power fluctuations.

Fiber-optic power meters are calibrated for standard transmission windows.

Wavelength and Frequency Measurements

Wavelength-measurement requirements vary widely, depending on the application. Precise knowledge of source wavelengths is critical in dense-WDM systems, where the transmission channels are closely spaced and must be matched to the transmission of demultiplexing components. Knowledge of the spectral response of system components also is vital in WDM systems, particularly for filters used in demultiplexing signals. On the other hand, wavelength need not be known precisely in systems carrying only one wavelength.

Wavelength is critically important in WDM systems.

Wavelength and Frequency Precision

So far, I have usually described wavelengths in round numbers, such as 1550 nm. That's common in optics; engineers who work with light think in terms of wavelength. However, wavelength is not as fundamental a characteristic of a light wave as its frequency. The wavelength depends on the refractive index of the medium transmitting the light; the frequency is constant. This is why standard channels and spacing for DWDM systems are specified in terms of frequency.

Earlier, you learned that the wavelength in a vacuum equals the speed of light divided by frequency, ν:

$$\lambda = \frac{c}{\nu}$$

However, this equation holds only in a vacuum. When the light is passing through a medium with refractive index n, the equation becomes

$$\lambda = \frac{c}{n\nu}$$

which means the wavelength decreases by a factor $1/n$.

Precise measurements and calculations are vital with WDM systems.

I have used round numbers in much of this book because they're usually good enough. Why punch 10 digits into your calculator when you can learn the same concept by punching only 2 or 3? Those approximations don't work for dense-WDM systems. You have to use exact numbers or you get into trouble. To understand why, run through a set of calculations first using the approximation of 300,000 km/s for the speed of light; then use the real value. Let's calculate the vacuum wavelength corresponding to the base of the ITU standard for WDM systems, 193.1 THz.

Using round numbers,

$$\lambda = \frac{3 \times 10^8}{(193.1 \times 10^{12})} = 1553.60 \text{ nm}$$

Using the exact value for c, the wavelength is

$$\lambda = \frac{2.997925 \times 10^8}{(193.1 \times 10^{12})} = 1552.52 \text{ nm}$$

The difference is less than 0.1%, but that's enough to shift the wavelength by more than one whole 100-GHz frequency slot. In short, the wavelength tolerances in dense-WDM systems are too tight to get away with approximations. You have to be precise.

Because of the importance of precision, frequency units may be used in measurements rather than the more familiar wavelength units. You should be ready to convert between the two when necessary, always using the precise formulas.

The wavelengths assigned to optical channels are the values in vacuum, not in air.

If you've been watching carefully, you will note that the wavelengths given so far are for light in a vacuum, where the refractive index is exactly 1. Why don't we use the wavelengths in air, which has a refractive index of 1.000273? It's primarily a matter of convention and simplicity. Physicists have long used vacuum wavelengths, and adjusted them slightly—when necessary—for transmission through air. If you wanted to convert frequency to wavelength in air, you would have to add a factor of *n* to all your equations, which could introduce errors. In addition, light often goes through other media, such as the glass in an optical fiber, and the refractive index of air varies with pressure and temperature.

From a physical standpoint, frequency is a more fundamental quantity. A light wave with a frequency of 193.1 THz oscillates at the same frequency in a vacuum, air, or glass. Yet the wavelengths differ because the refractive index differs among the three media. This is a major reason that the standards for DWDM optical channels are stated in frequency rather than wavelength.

Ways of Measuring Wavelength

Wavelength measurements can be absolute or relative.

It is not easy to measure wavelength precisely; it takes sophisticated instruments and carefully controlled conditions. Precise measurements became essential as DWDM systems packed channels close together, making it critical to separate and identify optical channels precisely. A few basic concepts are critical to understanding these measurements and the specific instruments covered in the next chapter.

Wavelength measurements can be absolute or relative. *Absolute measurements* tell you the precise wavelength (or frequency) of a light source. *Relative measurements* tell you the difference between the wavelengths of two light sources, often in frequency units. In general, relative comparisons are easier to make.

In practice, absolute measurements are made by comparing the wavelength with some well-defined standards of length or frequency. One way is to monitor changes in interference in two arms of an interferometer as the length of one is changed; another is to measure the difference in frequency between the unknown source and a standard, such as a laser with precisely defined wavelength.

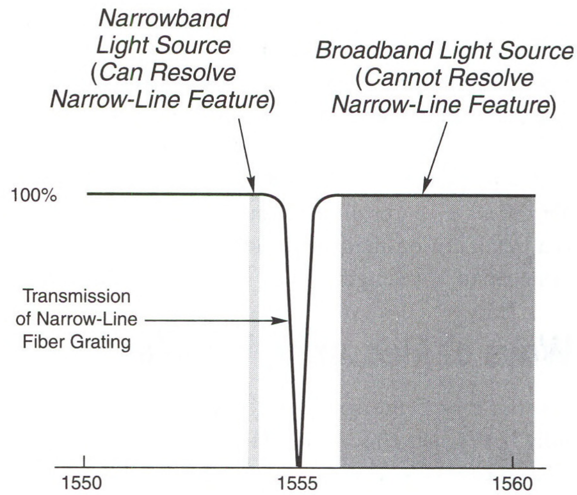
The accuracy of both absolute and relative measurements depends critically on calibration of the instruments, accuracy of the standards, and the comparison process. For example, precise measurements require accounting for the fact that air has a refractive index of 1.000273 at room temperature near 1550 nm. Although that number is only slightly higher than the refractive index of a vacuum, the small wavelength shift corresponds to a frequency difference of about 50 GHz in the 1550 nm window. That's significant for DWDM systems.

Linewidth Measurements

In addition to measuring the central wavelength of a laser source, you often need to measure the range of wavelengths in the signal, called the *linewidth* or *spectral width*. Where fiber dispersion is an issue or where a DWDM system carries closely spaced wavelengths, the linewidth should be small and often is measured in frequency units—for example, 150 MHz for a temperature-stabilized DFB laser emitting continuously. On this scale, frequency units are more convenient than wavelength; at 1550 nm, 100 GHz is about 0.8 nm, so 150 MHz is about 0.0012 nm. (External modulation adds to that linewidth.)

At lower speeds, where dispersion is not a critical concern, such as where a simple diode laser is modulated directly, the linewidth is much larger and is generally measured in wavelength units. In this case, wavelength units are more convenient.

FIGURE 17.5
Only a narrowband source can measure transmission of a narrow-line demultiplexer.



Spectral Response Measurements

Spectral response measures how systems and components respond to different wavelengths.

In addition to knowing the wavelength of the transmitter, you need to know how a fiber-optic system and its components respond to different wavelengths. This is called *spectral response.* For most components, the most important response is loss or attenuation as a function of wavelength. In the case of filters, multiplexers, and demultiplexers, you need to know how light is divided as a function of wavelength. That is, you need to know how much light is routed in different directions at various wavelengths. For optical amplifiers, the important feature is gain as a function of wavelength.

Spectral response measurements require a properly calibrated light source that emits a suitably narrow range of wavelengths. Figure 17.5 illustrates the problem by comparing two light sources with the transmission of a fiber Bragg grating that selectively reflects at 1555 nm for wavelength-division demultiplexing. A narrow-line source such as a tunable laser can accurately measure the response of the fiber grating, but a broadband source cannot, because its light contains a range of wavelengths much broader than the range of wavelengths the grating reflects.

Phase and Interference Measurements

Phase measures a light wave's progress in its oscillation cycle.

In Chapter 2 you learned that light waves have a property called *phase.* Recall that a light wave consists of an electric field and a magnetic field, each of which periodically rise and fall in amplitude, as shown in Figure 17.6. The amplitude varies in a sine-wave pattern, so the position in that cycle is measured as an angle, in degrees or radians. One wavelength is a complete cycle of 360° or 2π radians. Normally the phase is measured from the point where the amplitude begins increasing from zero. Amplitude peaks at 90°, returns to zero at 180°, has a negative peak at 270°, then returns to zero at 360°.

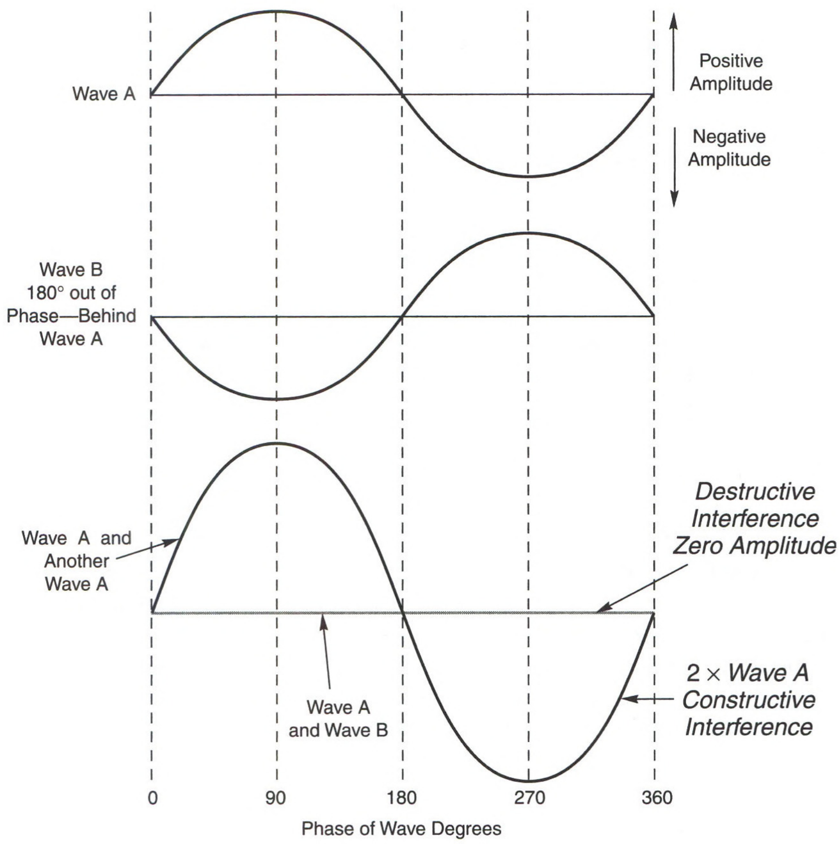


FIGURE 17.6
Phase and interference of light waves.

The absolute phase of a light wave is difficult to measure, but the relative phase can be measured simply by interferometry if the light is coherent. In Chapter 16, you learned that the operation of many fiber-optic modulators and switches depends on phase shifts between light traveling through two parallel arms. The same principle is used to measure phase shift. A laser beam is split, then recombined and the power is measured. If the light beams add constructively, the relative phase shift is 0°. If the beams add destructively, the phase shift is 180°. Other values can be interpolated.

In practice, the phase shift usually is measured relatively, as an angle between 0° and 360° (a whole wave), although the actual shift in phase may be a number of wavelengths plus an angle between 0° and 360°. That's a matter of convenience. Relative phase shift is easier to measure, and usually the relative shift is more important for device operation. The absolute phase shift between two waves can be measured using devices that count the number of interference peaks, but it's rarely necessary for fiber optics.

Actual phase measurements are messier than our simple example. Two beams must be equal in amplitude and precisely 180° out of phase to cancel each other completely by destructive interference. They also must be perfectly coherent, with exactly the same wavelength.

Those conditions are virtually impossible to obtain, so in practice phase shift measurements are made by looking for the maximum and minimum.

Polarization Measurements

Polarization is the alignment of the electric field in a light wave.

The polarization direction of a light wave is defined as the orientation of the electric field, which automatically sets the direction of the magnetic field that is perpendicular to it. Light waves with their electric fields in the same linear plane are *linearly polarized.* If the field direction rotates along the light wave, the light is *elliptically* or *circularly polarized.* If the fields are not aligned with each other in any way, the light is *unpolarized.*

Several polarization characteristics significant in fiber-optic systems may require measurements. The simplest in concept is the direction of the polarization. This can be measured by passing the light through a polarizer and rotating the polarizer to see at what angles the transmitted light is brightest and faintest.

Polarization dependence arises when the loss or gain of a component depends on the polarization of the light passing through it. This can create a problem by modulating the light signal according to its polarization, which introduces noise into the system.

Loss or gain may depend on polarization.

Polarization-dependent loss measures the maximum differences in attenuation for light of various degrees of polarization. For example, if an optical component has 3-dB attenuation when transferring horizontally polarized light and 6 dB for vertically polarized light, it has a polarization-dependent loss of 3 dB—if those are the maximum and minimum values for attenuation. Polarization-dependent loss can be measured by adding polarization analyzers to conventional loss measurement instruments.

Polarization-dependent gain is a variation in gain for light of different polarizations passing through an optical amplifier, the inverse of polarization-dependent loss. It is particularly important for semiconductor optical amplifiers.

Polarization-mode dispersion (PMD) is the spreading of pulses arising from the dispersion of light between the two orthogonal polarization modes, as described in Chapter 5. The degree of PMD is not constant for a fiber; it varies statistically with time, depending on environmental conditions. This means that measurements of PMD have to be made over a period of time. Specialized instruments can measure the instantaneous polarization direction, the instantaneous PMD, and the differential group delay or pulse spreading caused by PMD.

Time and Bandwidth Measurements

Bandwidth and time measurements indicate transmission capacity.

As you learned in Chapter 5, system bandwidth is limited by the spreading or dispersion of pulses in the fiber, transmitter, and receiver. This means that time and bandwidth measurements in fiber-optic systems are related. You can think of them as different ways to measure the information transmission capacity of the system. Time measurements directly measure how fast the system can respond to a pulse. Bandwidth depends on this time response, but it also can be measured directly.

Pulse Timing

Figure 17.7 shows the key parameters in measuring pulse timing.

- *Rise time* is the time the signal takes to rise from 10% to 90% of the peak power.
- *Pulse duration* normally is the time from when the signal reaches half its maximum strength to when it drops below that value at the end of a pulse. This is called *full width at half maximum*, abbreviated FWHM.
- *Fall time* is the interval the signal takes to drop from 90% to 10% of peak power.
- *Pulse spacing* or *pulse interval* is the interval between the start of one pulse and the point where the next should start. If the signal is on for 1 ns and there is a 1-ns delay before the next pulse can start, the pulse spacing is 2 ns. The pulse spacing means the interval between transmitting one data bit and transmitting the next, whether the bits are "0s" or "1s."
- *Repetition rate* is the number of pulses or data bits transmitted per second, which in practice is the pulse spacing divided into 1:

$$\text{Repetition rate} = \frac{1}{\text{pulse spacing}}$$

Thus if the pulse spacing is 1 ns, the repetition rate is 1 Gbit/s.

- *Jitter* is the uncertainty in the timing of pulses, typically measured from the point at which they should start.

Measurements are made by feeding the optical signal to a detector, which generates an electronic output that instruments measure. This means that time response measured for the light pulse also includes the time response of the detector and the instrument. This effect can be significant at high data rates and must be considered in making fast measurements.

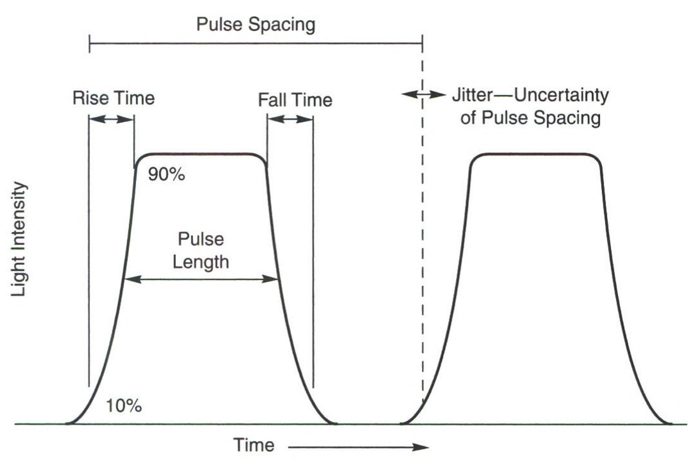


FIGURE 17.7
Pulse timing.

Repetition rates in even the slowest fiber-optic systems are extremely fast on a human scale—a million or more pulses per second—so you cannot see signal-level variations in real time. They are recorded on an oscilloscope or other display, which allows you to see events that are too fast for your eyes to perceive.

Bandwidth and Data Rate

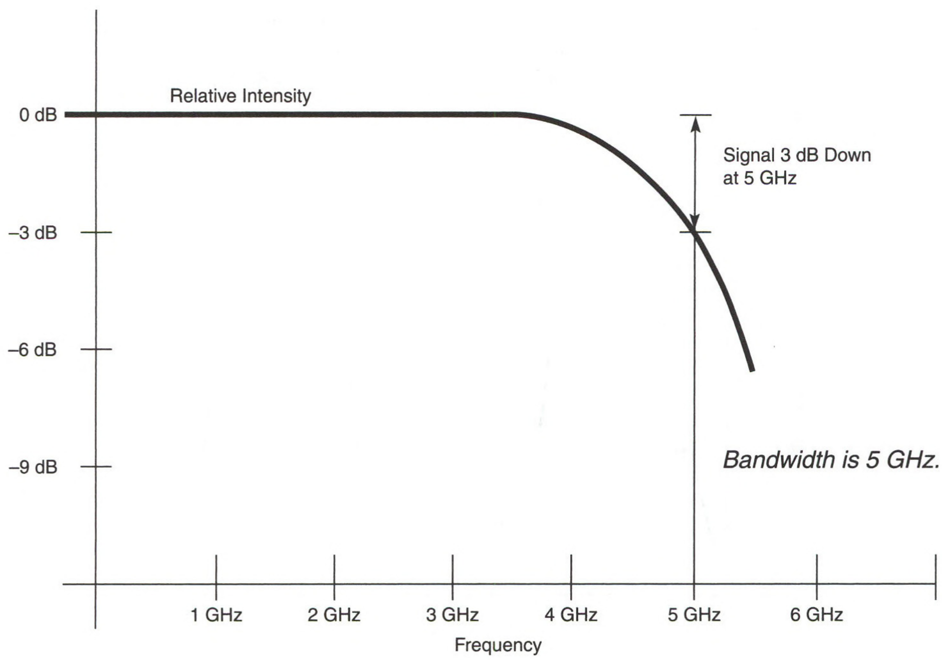
Bandwidth and data rate of communication systems differ in subtle but important ways. *Bandwidth* usually is an analog measurement of the highest signal frequency the system can carry. *Data rate* or *bit rate* is a digital measurement of the maximum number of bits per second actually transmitted. (*Baud* strictly speaking refers to the number of signal transitions per second, which may not equal data rate.) Both bandwidth and data rate deserve a bit more explanation.

Signal bandwidth measures analog transmission capacity.

The carrier frequency in an analog system is modulated with an analog signal spanning a range of frequencies. Typically it cuts off at some low minimum frequency, but the most important limit is the upper frequency cutoff, which arises from dispersion effects in fiber-optic systems. The attenuation increases with signal frequency, and the bandwidth limit normally is defined as the point where signal amplitude is reduced 3 dB, as shown in Figure 17.8. As you can see in the figure, higher frequencies suffer more attenuation.

Note that the signal bandwidth is distinct from the range of wavelengths transmitted by the fiber. You should think of the range of wavelengths as the optical bandwidth, distinct from the signal bandwidth. Optical attenuation is not the same as signal attenuation. An optical amplifier can compensate for optical attenuation by increasing the optical power,

FIGURE 17.8
Frequency response of an analog fiber-optic system.



THINGS TO THINK ABOUT

Types of Bandwidth

We've used the word "bandwidth" to describe fiber-optic systems in a few different ways. Fibers transmit light, and have an optical bandwidth of roughly 800 to 1600 nm. They don't transmit microwaves at all. Yet Figure 17.8 shows what looks like the attenuation of microwave signals passing through fibers. What's going on?

The microwave signals modulate the beam of light by varying the light intensity at microwave frequencies. That is, the microwaves are encoded as variations in the light intensity, just as sound waves are encoded as variations in electricity passing through phone wires. The fibers don't actually transmit microwaves, just as phone wires don't actually transmit sound waves.

The microwave attenuation shown in Figure 17.8 arises from dispersion, not light attenuation. It's easiest to visualize for digital pulses, which dispersion spreads out as they pass through the fiber. Eventually the pulses blur together, which means the microwave-frequency signal has faded away. The light is still there, but the microwave signal has been attenuated to the point where it can't be distinguished from noise.

Recall that square digital pulses actually are the sum of a series of sine waves at harmonics of the square-wave frequency:

$$f(t) = C(\sin \omega t + \frac{1}{3} \sin 3\omega t + \frac{1}{5} \sin 5\omega t + \ldots)$$

The highest frequencies give the square wave its sharp edges. Dispersion attenuates those high frequencies the most, rounding the edges of the signal until eventually they are humps that look more like sine waves at the base frequency. Good discrimination circuits can identify those rounded pulses, so you don't need to receive the higher harmonics, only the base frequency (e.g., 1 GHz for a 1-Gbit/s signal).

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but it can't make up for signal attenuation, which is caused by dispersion. Dispersion doesn't reduce the optical power, but it does blur the signal together, reducing the signal intensity that can be detected above the background noise.

The bit rate or data rate in bits per second is the speed limit of digital systems. The upper limit of the bit rate is determined by the maximum error rate that is considered acceptable. The desired error rate depends on the application. Typically it's one bit in a billion (10^{-9}) or one in a trillion (10^{-12}) for data and voice transmission, but it may be lower for music or video transmission.

Analog bandwidth does not equal digital data rate.

Analog bandwidth and digital data rate are related, but not equivalent. Communications theory shows that a digital signal can be considered as the sum of signals at many different frequencies (called *harmonic frequencies*) that are integral multiples of the fundamental frequency—the signal bit rate. An ideal square wave is made up of a series of analog harmonics of the fundamental frequency:

$$f(t) = C(\sin \omega t + \frac{1}{3} \sin 3\omega t + \frac{1}{5} \sin 5\omega t + \ldots)$$

The highest frequencies give the square wave its sharp edges. They suffer the most attenuation when the signal is transmitted, so digital pulses first lose their sharp corners, then gradually become more like sine-wave humps. The discrimination circuits described in Chapter 11 are used to tell the humps of attenuated signals from the bumps of noise.

An analog transmission system can carry signals at a range of frequencies. That is, it responds to a certain range, analogous to the nominal 20 to 20,000 Hz response of the human ear. Normally, the bandwidth of fiber-optic systems is limited only at high frequencies. If you measure the signal received as a function of frequency, it drops at high frequencies, as shown in Figure 17.7. Typically the bandwidth is defined as the point where response has dropped by one-half or 3 dB—about 5 GHz in Figure 17.7.

As you can see from Figure 17.7, the system does transmit higher frequencies, but it attenuates them more strongly, so their intensity at the output is much weaker. Thus signals at 5.5 GHz are attenuated about 3 dB more than those at 5 GHz, and 6 dB more than those at 3 GHz. In practice, the higher attenuation means you can't count on the signals reaching the receiver in usable form. The usability of an analog signal is measured by the signal-to-noise ratio, described later in this chapter.

Data rate measures the speed of digital systems.

The speed limit of digital systems is measured as a *data rate* or *bit rate*, that is, how many bits can be transmitted through the system per second. The data rate response is not as easy to plot as the frequency response. In practice, the quality of a digital signal is measured as a *bit error rate*, also described later in this chapter. The poorer the signal quality, the more bits are received incorrectly. The maximum data rate is the highest transmission speed that meets error-rate specifications.

Signal Quality Measurements

Transmission quality of telecommunication systems can be assessed by comparing the output signal to the input. Different measurements are used for analog and digital systems.

Signal-to-Noise Ratio

Signal-to-noise ratio measures analog transmission quality.

Quality of an analog communication system is measured by the ratio of signal power to noise. The higher the *signal-to-noise ratio* (often written S/N), the higher the quality of the signal. What is an acceptable signal-to-noise ratio depends on the application and the user. The background hiss on analog audio cassette tapes is a good example; you notice it more in quiet passages of classical music in a quiet room than you would listening to loud rock music in a speeding car with the windows down. Users of analog transmission systems may set standards that define acceptable signal-to-noise levels. That is done by the cable television industry, the main user of analog fiber-optic systems.

Signal-to-noise ratio also can assess the performance of individual analog components. Optical amplifiers are important examples, where the ratio of the output signal to the background noise determines performance. The concept is fairly intuitive; the more signal and the less noise, the better. Typically signal-to-noise ratios are measured in decibels.

Bit Error Rate

The fraction of incorrect bits is the bit error rate.

Bit error rate (or ratio) measurements compare digital input and output signals to assess what fraction of the bits are received incorrectly. They offer a quantitative measurement of signal quality.

In practice, a special instrument generates a randomized bit pattern, which is transmitted through the system. The total number of bits transmitted are counted. So are errors that occur when the signal bit interpreted by the receiver does not match the transmitted signal. The more wrong bits, the worse the transmission quality.

As you would expect, the bit error rate increases as received power drops, as well as when the system approaches other performance limits such as maximum data rate. The increase in error rate is quite steep, and can be more than a factor of 100 when the input signal drops by 1 dB, if the system is operating near its performance limits. Other factors may set a minimum bit error rate when input power is adequate, and excess power can cause errors by overloading the receiver.

Users set standards for acceptable bit error rates. A typical target for telecommunications and data transmission is 10^{-12} (one error in a trillion bits). Higher error rates may be acceptable in other applications, such as video transmission.

Eye-Pattern Analysis

One popular way to assess performance of digital fiber-optic links is to superimpose a series of pulses on an oscilloscope display. This is called *eye-pattern analysis* because it produces the eye-shaped pattern shown in Figure 17.9.

An *eye pattern* superimposes waveforms of successive bits to assess signal quality.

The oscilloscope traces each received pulse on the screen. If there was no noise, each trace would follow exactly the same line, overlaying other pulses. Adding noise to the signal causes the intensity to vary randomly during the signal pulse, blurring the trace vertically. Likewise, jitter that varies the time when pulses arrive at the receiver spreads the lines horizontally.

What the eye pattern really measures is the repeatability of pulses reaching the instrument. The better the transmission quality and the more uniform the received pulses, the more open the eye will appear. If the eye starts to close—leaving less clear space in the center—it indicates that transmission errors are likely because it's becoming hard to tell the high points of the signal (the top of the eye) from the low points (the bottom of the eye).

The eye pattern measures pulse repeatability.

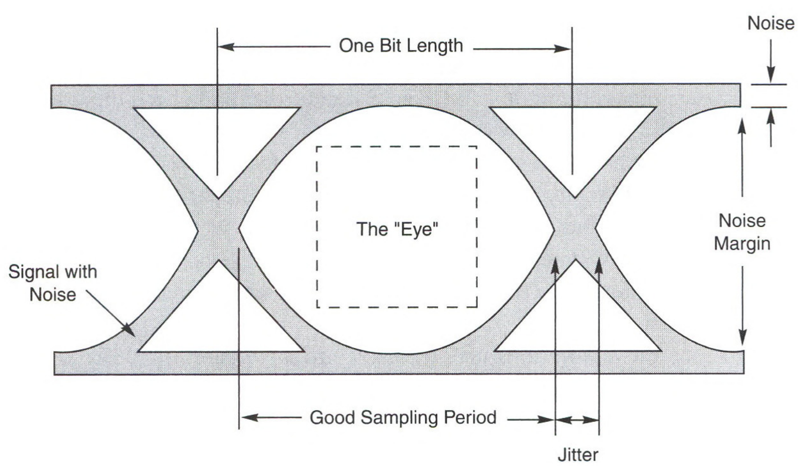

FIGURE 17.9
An eye pattern.

Careful interpretation of the eye pattern can yield important information on fiber-link performance. Some important points for interpreting eye patterns include:

- Height of the central eye opening measures noise margin in the received signal.
- Width of the signal band at the corner of the eye measures the jitter.
- Thickness of the signal line at the top and bottom of the eye is proportional to noise and distortion in the receiver output.
- Transitions between the top and bottom of the eye show the rise and fall times of the signal.

Fiber-Specific Measurements

So far I have described two broad classes of measurements: optical quantities that apply to fiber optics and communications system performance.

Another broad class of measurements is specific to optical fibers and fiber-optic systems. It's impossible to cover them comprehensively in a general introduction to fiber optics, so I will concentrate on a few key fiber parameters, such as attenuation and power in fibers. I will begin with general measurement concepts, then turn to important fiber-optic procedures. Chapter 18 describes important types of test equipment and outlines simple troubleshooting procedures.

Calibration

Calibration is essential for verifying the accuracy of measurements.

Calibration is an essential element of any measurement procedure. You calibrate the bathroom scale when you check that it reads zero before you stand on it to weigh yourself. When you make electrical measurements, you check that the current meter reads zero when the current probes are not in contact with the circuit.

For more precise measurements, you want to make sure the readings are accurate at more points on the scale. To double-check your bathroom scale, you could place a hundred-pound weight on it. To check a current meter, you could connect it to a standard current source designed to deliver one milliampere.

To be really exacting, you might want to go a step further and check the source of your calibrations. Instead of borrowing weights from your neighbor's barbells to test your bathroom scale, you might borrow a set of weights from the local university, which have been compared against precise standard masses. Then you could compare the university's weights against the barbells and find, for example, that the barbell weights weigh 97.5 pounds instead of the 100 pounds stated on the box.

This sort of calibration and comparison is done for precision measurements. Check a good set of test instruments, and you will find dates on which they were calibrated, and you may find that the calibrations are "traceable" to an organization like the National Institute of Standards and Technology, which provides measurement standards in the United States. You don't need this sort of exacting precision for every fiber-optic measurement, but it's essential for precision work. For example, in a short data link you might only need to know optical power to within 20%. However, in a state-of-the-art DWDM system with 50-GHz channel spacing, you may need to measure wavelength of individual light sources with accuracy better than 0.01% to make sure channels are properly spaced.

Fiber Measurement Standards

Serious fiber-optic measurements often refer to cryptic-seeming codes, such as EIA/TIA-455A. These codes identify standards written by industry and professional organizations, which specify how to make the measurements so the results are comparable to those made by other groups.

Measurement standards assure that results are compatible.

Standards often go into excruciating details in specifying the techniques and equipment used for particular measurements. However, those details can be as important in getting the right answer as not leaning against the sink can while standing on your bathroom scale. The essential point is to make sure that everyone's measurements are comparable and repeatable. Fiber specialists have found out the hard way that results can differ depending on whether the labs are or are not air-conditioned.

Chapter 20 talks more about fiber-optic standards, but the details are beyond the scope of this book. The number of standards is expanding, with scope ranging from the fiber itself to details of physical packages and signal formats. Table 17.2 lists some major groups that issue multiple standards. A number of other organizations have formed to produce standards for specific applications or types of devices, such as 10-Gigabit Ethernet or Xenpak transceivers, but the resulting standards usually are administered by one of the groups listed in the table.

Table 17.2 Standards organizations

ANSI	American National Standards Institute	*www.ansi.org*
ASTM	American Society for Testing & Materials	*www.astm.org*
ATIS	Alliance for Telecommunications Industry Solutions	*www.atis.org*
EIA	Electronics Industries Alliance	*www.eia.org*
ICEA	Insulated Cable Engineers Association	*www.icea.net*
IEC	International Electrotechnical Commission	*www.iec.ch*
IEEE	Institute of Electrical and Electronics Engineers	*www.ieee.org*
ITU	International Telecommunications Union	*www.itu.int*
NEC or NFPA	National Electrical Code (administered by National Fire Protection Association)	*www.nfpa.org*
NIST	National Institute for Standards and Technology	*www.nist.gov*
Telcordia	Telcordia Technologies (formerly Bellcore)	*www.telcordia.com*
TIA	Telecommunications Industry Association	*www.tiaonline.org*
UL	Underwriters Laboratories	*www.ul.com*

Measurement Assumptions

One reason that standards describe procedures in so much detail is to limit the number of assumptions made in making measurements. We inevitably make implicit and explicit assumptions, and sometimes those assumptions can lead to the wrong results.

If you check that your bathroom scale reads zero when nothing is on it, and 100 pounds with calibrated weights, you still make an assumption when you weigh yourself. You assume that the rest of the scale is accurate, and that if you go 50 steps up from 100 pounds, the scale is accurately measuring you at 150 pounds. However, it's possible that the scale might be a few pounds off, so what reads 150 pounds is actually 145 or 155 pounds.

We also make many assumptions in fiber optics, and some of them also may be wrong. It's reasonable to assume that light is distributed the same way along the length of a single-mode fiber, but not in a multimode fiber. Light may have to travel through a kilometer of graded-index fiber before distributing itself evenly among all the possible transmission modes. Differences between the real and the assumed mode distribution can affect measurements of the fiber's light-acceptance angle and numerical aperture. Likewise, we might assume that connector loss is identical in both directions, but be fooled because the core of one fiber is slightly smaller than that of the other, so the loss is 0.3 dB higher in one direction than in the other.

Careful adherence to standards can avoid pitfalls, which can be subtle in more sophisticated measurements.

Fiber Continuity

Fiber continuity checks can verify system function. The simplest test is to see if light can pass through the fiber.

A major concern in installing and maintaining fiber-optic cables is system continuity. If something has gone wrong with the system, you need to check if the cable can transmit signals. If it can, you know you have another problem. If it can't, you need to find the break or discontinuity. In some cases, the break may be obvious—a cable snapped by a falling tree limb or a hole dug by a careless contractor. However, such damage is not always obvious, and the cable route may not be readily accessible.

Early fiber technicians developed a quick-and-dirty test of fiber continuity. One shined a flashlight into the fiber, and a second on the other end looked to see if any light emerged. That is far from ideal because flashlight beams do not couple efficiently into optical fibers. It also requires people at each end of the fiber—one to send the light and the other to look for the transmitted light—and those people must be able to communicate with each other.

Now specialized instruments can do a much better job, often without requiring people on both ends. You will learn more about them and troubleshooting techniques in Chapter 18. Optical time-domain reflectometers (OTDRs) and optical fault indicators send pulses of light down the fiber and look for reflections that indicate a fault. Optical test sets measure power transmission. Fiber identifiers can tell if exposed fibers are carrying signals (they work by bending the fiber and observing light that leaks out at the bend). Visible fault identifiers send visible red light through the fiber, and visual inspections show if any is leaking out.

Optical Power

Measurements of optical power require knowing the wavelength and duty cycle.

Optical power is the quantity most often measured in fiber-optic systems. I described the basic principles earlier. The power may be output from a transmitter or optical amplifier, power emerging from a length of optical fiber, or power in some part of a system. The wavelength must be known so that the detector can be calibrated for that wavelength. Duty cycle—the fraction of the time the light source is on—should also be known to interpret properly measurements of average power. The usual assumption is 50% (half on, half off) for digital modulation, but under certain circumstances that may be far off (e.g., if a series of 1s is being transmitted in NRZ code).

Normally, power is measured where the light emerges from a light source or fiber. Fiber-optic power meters collect the light from the fiber through an optical connector, which directs the light to a detector. Electronics process the detector output and drive a digital display that shows the power level in linear units (nanowatts to milliwatts) or in dB referenced to either 1 mW or 1 μW. Measurement ranges are automatically switched across the dynamic range, which is typically a factor of one million. Typical measurement accuracy is ±5%.

Measuring optical power stops the beam, because it's absorbed by the detector. If you want to sample the power level in a transmitted signal, you need a coupler to divert a calibrated fraction of the light to a detector and transmit the rest.

It is important to keep input power within the dynamic range of the power meter. Excessive powers won't be measured correctly, and in extreme cases, excess power can damage some detectors.

Attenuation

Attenuation is the most important property of passive optical components, because it determines what part of an optical signal is lost within the component and how much passes through. It is always a function of wavelength, although the wavelength sensitivity varies widely. In fibers, the variation with wavelength is significant; in some other components, it is negligibly small.

Optical test sets measure cable loss.

As you learned earlier, attenuation is measured by comparing input and output powers. Figure 17.10 shows a standard way to measure cable loss using an optical test set—which includes a light source and transmitter. First the light source is connected to the power

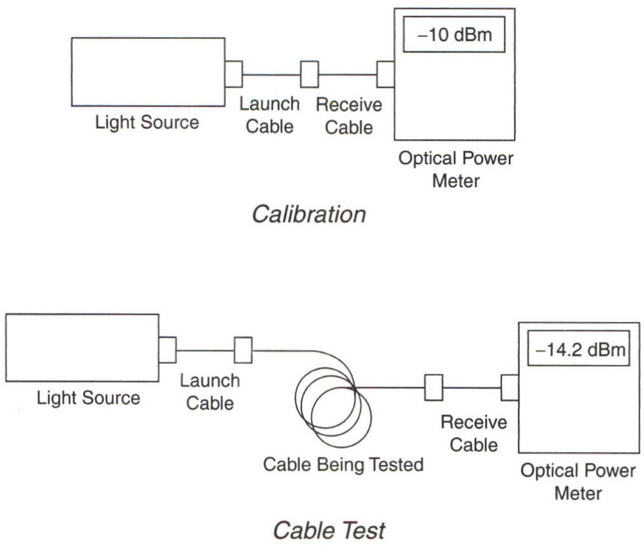

FIGURE 17.10
Cable loss measurement.

meter through a short launch cable, and the power is adjusted to a convenient level (-10 dBm in this case). Then a short receive cable is added between the launch cable and the power meter; a power change no more than 0.5 dB verifies the receive cable is good. The meter is again adjusted to the desired level. Then the cable to be tested is connected between launch and receive cables and the power it transmits is read (-14.2 dBm in this case). The difference, 4.2 dBm, is taken as the total attenuation of the cable being tested, including fiber, connectors, and splices. For more precise measurements, the loss should be measured in both directions through the test cable, because connector attenuation may differ slightly in the two directions.

The same principles can be used to measure the attenuation of other components, such as couplers, or of segments of cable installed in a system. If cable ends are located at different places, the tests can be performed by technicians working at both ends, one with a light source and the other with a power meter, or by temporarily installing a "loop-back" cable to send the signal back to the origination point through a second fiber. Inevitably, small losses are measured less accurately than large ones.

Precise measurements of fiber attenuation rely on cutting back fibers to compare power emerging from short and long lengths.

This simple comparison technique is adequate for most purposes, but it does not precisely measure pure fiber loss, because it includes loss within the connectors at each end. More precise measurements of fiber loss alone require the cut-back technique. First, power transmission is measured through the desired length of fiber. Then the fiber is cut to a short length (about a meter) and the power emerging from that segment is measured with the same light source and power meter. Taking the ratio of those power measurements eliminates input coupling losses (which occur in both measurements), while leaving the intrinsic fiber transmission loss (which is present only in the long-fiber measurement).

The *cut-back* method is more accurate for single-mode fibers than for multimode fibers, because of the way mode distribution changes along the fiber. Accurate measurement of long-distance attenuation of multimode fibers requires use of a mode filter to remove the higher-order modes that gradually leak out of the fiber. However, this won't accurately measure the loss of short multimode fibers, which depends on propagation of the high-order modes.

One special problem with single-mode fibers is that light can propagate short distances in the cladding, throwing off measurement results by systematically underestimating input coupling losses. To measure true single-mode transmission and coupling, fiber lengths should be at least 20 or 30 m.

Mode-Field and Core Diameter

Mode-field diameter is the region occupied by light in a single-mode fiber.

As you learned earlier, fiber core diameter can vary because of manufacturing tolerances. In addition, mode-field diameter—the diameter of the region occupied by light propagating in a single-mode fiber—is somewhat larger than the core diameter. These quantities can be measured.

Practical interest in the mode-field and core diameters depends on the distribution of light, and measurements are, therefore, based on light distribution. One approach is to scan across the end of the fiber with another fiber of known small core diameter, observing variations in light power collected by the scanning fiber. Other approaches rely on observing the spatial distribution of light near to or far from the fiber—the near-field and far-field intensity patterns. Those distributions of optical power can be used to calculate the core diameter.

A related quantity important for both single- and multimode fibers is the *refractive-index profile*, the change in refractive index with distance from the center of the fiber. This also is measured by examining the light distribution across the fiber.

Numerical Aperture and Acceptance Angle

The numerical aperture measures how light is collected by an optical fiber and how it spreads out after leaving the fiber. It measures angles, but not directly in degrees or radians. Although NA is widely used to characterize fiber, it isn't NA that is measured, but the fiber acceptance angle, from which NA can be deduced.

Numerical aperture is not measured directly; it is calculated from the acceptance angle.

Numerical aperture and acceptance angle are most important for multimode fibers. As mentioned earlier, measured numerical aperture depends on how far light has traveled through the fiber, because high-order modes gradually leak out as light passes through a fiber. The measured numerical aperture can be larger for shorter fibers, which carry a larger complement of high-order modes, than it will be for long fiber segments. Measurements are made by observing the spread of light emerging from the fiber.

Cutoff Wavelength

Cutoff wavelength, the wavelength at which the fiber begins to carry a second waveguide mode, is an important feature of single-mode fibers. The measured effective cutoff wavelength differs slightly from the theoretical cutoff wavelength calculated from the core diameter and refractive-index profile. As with core and mode-field diameter, cutoff wavelength is a laboratory rather than a field measurement.

Cutoff wavelength is measured by observing where stripping out the second-order mode causes an increase in loss.

Normally, the cutoff wavelength is measured by arranging the fiber in a test bed that bends the fiber a standard amount. Fiber attenuation as a function of wavelength is measured twice. First, the fiber is bent in a manner that causes the second-order mode to leak out almost completely. Second, the fiber is arranged so it transmits both first- and second-order modes. These two measurements are compared, giving a curve such as the one in Figure 17.11, which shows

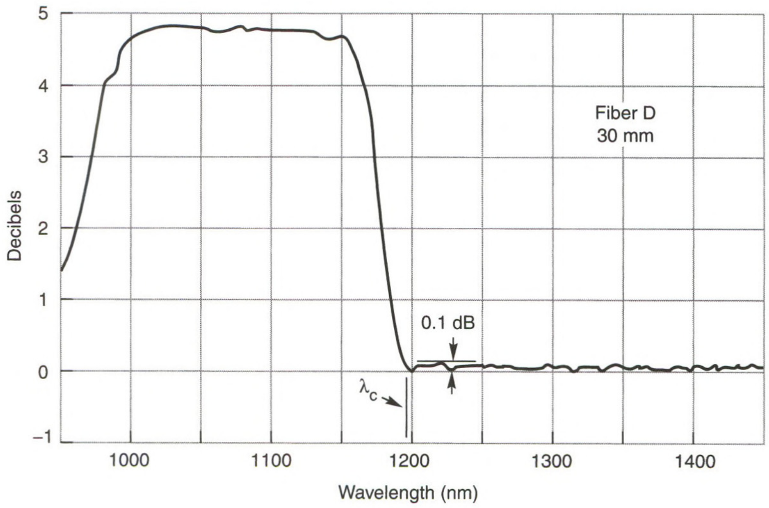

FIGURE 17.11
Measurement of effective cutoff wavelength. (Courtesy of Douglas Franzen, National Institute of Standards and Technology)

excess loss as a function of wavelength. In this case, λ_c is the effective cut-off wavelength, which is defined as the wavelength above which second-order mode power is at least a certain amount below the power in the fundamental mode. The measurement finds this value by locating the point where excess loss caused by stripping out the second-order mode is no more than 0.1 dB.

What Have You Learned?

1. Each photon has a characteristic energy, defined as Planck's constant (h) times the frequency (v). Photon energy also equals hc/λ, where c is the speed of light and λ is the wavelength.
2. Optical power measures the transfer of light energy, and is defined as the change in energy with time. Power is proportional to the number of photons passing a given point per unit time.
3. Optical power is proportional to the square of the light wave amplitude.
4. Optical power can be measured in decibels relative to a power level. The units dBm are powers relative to 1 mW; dBμ measures power relative to 1 μmW.
5. Peak power is the highest level in an optical pulse; average power is the average over a longer interval, typically a second or more.
6. Pulse energy can limit communications because detectors must receive a minimum amount of energy to recognize a pulse.
7. Fiber-optic power meters are calibrated for wavelengths used in fiber systems; they measure average power.
8. Accurate conversions between wavelength and frequency are critical in DWDM systems, where the channels are based on *frequencies*, not wavelengths. Always use the exact value for the speed of light in a vacuum in conversions, 2.997925×10^8 m/s, and remember that wavelengths conventionally used are those in a vacuum, not in air or glass.
9. Wavelengths can be measured absolutely, or relative to another wavelength.
10. Phase measures a light wave's progress in its 360° oscillation cycle. It is measured relative to the phase of other light waves.
11. Polarization measures the alignment of electric fields in light waves. Polarization-dependent loss can affect system performance.
12. Bandwidth measures the highest analog frequency a system can transmit. The speed of digital systems is measured by the maximum data rate that can be transmitted.
13. Signal-to-noise ratio measures analog transmission quality. Bit error rate measures the quality of digital transmission.
14. An eye pattern superimposes waveforms of successive bits to assess signal quality. The more "open" the eye, the more similar the successive pulses are, and the better the transmission quality.

15. Measurement standards assure that results are compatible. Calibration verifies measurement accuracy.
16. Precise procedures are needed to measure fiber or cable attenuation accurately.

What's Next?

Chapter 18 covers test equipment and troubleshooting techniques.

Further Reading

Dennis Derickson, ed., *Fiber Optic Test and Measurement* (Prentice Hall PTR, Upper Saddle River, NJ, 1998)

Edward F. Zalewski, "Radiometry and Photometry," section 24 in Michael Bass, ed., *Handbook of Optics,* 2nd ed., Vol. 2 (McGraw-Hill, New York, 1995)

Catalogs of test equipment manufacturers typically include tutorials on fiber-optic test and measurement. Two good ones are:

Agilent Technologies, *Lightwave Test and Measurement Catalog* (see *www.agilent.com*)

Exfo Electro-Optical Engineering, *Lightwave Test & Measurement Reference Guide* (see *www.exfo.com*)

Questions to Think About

1. A 1-Gbit/s signal has an average power of 1 μW at the receiver. What is the average energy in each pulse?
2. A 10-Gbit/s signal has an average power of 1 μW at the receiver. What is the average energy in each pulse?
3. The wavelength being transmitted in Questions 1 and 2 is 1550 nm. How many photons does each pulse contain?
4. Suppose these systems were operating at a wavelength of 850 nm. How many photons would be in each pulse at average power of 1 μW and data rates of 1 and 10 Gbit/s? Assuming that noise levels are constant relative to photons per bit, how would that affect signal-to-noise ratios?
5. The air pressure at the Keck Telescope on the top of Mauna Kea in Hawaii, 4.2 km above sea level, is about 60% of that at sea level. The refractive index of air is 1.000273 at standard temperature and pressure. Assume that the refractive index of air is proportional to density. What are the wavelengths of light with a frequency of 193.1 THz in a vacuum, in air at sea level (standard temperature and pressure), and at the top of Mauna Kea? Be sure to use the exact value of the speed of light, 299,792.5 km/s. How does this compare

with the shift in wavelength between optical channels at 50 GHz spacing at the same frequency?

6. What is a frequency difference of 100 GHz equivalent to at the 850 nm wavelength of gallium arsenide lasers?

Chapter Quiz

1. Optical power is
   a. light intensity per square centimeter.
   b. the flow of light energy past a point.
   c. a unique form of energy.
   d. a constant quantity for each light source.
2. What measures power per unit area?
   a. irradiance
   b. intensity
   c. average power
   d. radiant flux
   e. energy
3. A digitally modulated light source is on 25% of the time and off 75% of the time. Its rise and fall times are instantaneous. If its average power is 0.2 mW, what is the peak power?
   a. 0.2 mW
   b. 0.4 mW
   c. 0.8 mW
   d. 1.0 mW
   e. impossible to calculate with the information given
4. The light source in Problem 3 is left on for 10 s. How much energy does it deliver over that period?
   a. 0.2 mW
   b. 0.2 mJ
   c. 0.8 mJ
   d. 2 mJ
   e. 8 mJ
5. Light input to a 10-km long fiber is 1 mW. Light output at the end of the fiber is 0.5 mW. What is the fiber attenuation in dB/km?
   a. 0.3 dB/km
   b. 0.5 dB/km
   c. 1 dB/km
   d. 3 dB/km
   e. 5 dB/km

6. Optical power is proportional to the
   a. square of the optical intensity.
   b. square of the optical energy.
   c. wavelength times the speed of light.
   d. square of the voltage applied to the detector.
   e. square of the electric-field amplitude.

7. An old meter with its labels worn off measures the output of a 1550-nm laser transmitter at zero lumens even when you turn it to peak sensitivity. What's wrong?
   a. The laser is burned out.
   b. The meter is reading in radiometric units, which only measure power at 1300 nm.
   c. The meter is calibrated in photometric units, which only measure light visible to the eye.
   d. You are using a dead optical energy meter.
   e. You are using an electrical power meter.

8. Optical channels are spaced 50 GHz apart in a DWDM system. What wavelength difference does this correspond to at 1550 nm?
   a. 0.2 nm
   b. 0.4 nm
   c. 0.5 nm
   d. 0.8 nm
   e. 50 nm

9. A continuous 1-mW beam delivers light at 193.1 THz for one second. About how many photons is this equivalent to? Use a value of 6.626×10^{-34} J/Hz for Planck's constant *h*.
   a. 10^9 photons
   b. 193.1×10^9 photons
   c. 7.82×10^{12} photons
   d. 193.1×10^{12} photons
   e. 7.82×10^{15} photons

10. Pulse duration is
   a. the interval between the time the rising pulse reaches half its maximum height to the time the falling pulse drops below that height.
   b. the interval between successive peaks of the pulse.
   c. the time it takes the pulse to rise from 10% to 90% of its maximum value.
   d. half the cycle of a periodic sine wave.
   e. the time from the start of one pulse to the start of the next.

11. System bandwidth is measured as the
   a. number of bits per second transmitted with no errors.
   b. number of bits per second transmitted with a bit error rate of 10^{-12}.

c. maximum frequency transmitted with no decline in power from lower frequencies.

d. frequency at which power has dropped 3 dB from the power at lower frequencies.

e. wavelength at which power has dropped 3 dB from the power at lower wavelengths.

12. What is the standard measure for transmission quality in digital systems?

a. signal-to-noise ratio

b. bit error rate

c. attenuation from transmitter to receiver

d. 3-dB bandwidth

e. pulse interval

13. Jitter measures

a. rise time of a digital pulse.

b. duration of a digital pulse.

c. shaking of your test instruments caused by people walking through your lab.

d. uncertainty in bit error rate.

e. uncertainty in pulse timing.

14. What does an open eye pattern indicate?

a. good-quality transmission because a series of digital pulses are nearly identical

b. good-quality transmission because an analog carrier signal is at peak intensity

c. that a signal of at least one milliwatt is reaching the instrument

d. that the fiber is broken so it cannot transmit noise

e. that you have managed to stay awake through the whole chapter

15. What do you need to measure accurately the loss of a length of cable with connectors on each end?

a. an optical power meter

b. a light source and an optical power meter

c. a light source, an optical power meter, and a launch cable

d. a light source, an optical power meter, a launch cable, and a receive cable

e. a light source, an optical power meter, a launch cable, a receive cable, and a bit error rate test set