CHAPTER 10

Transmitters

About This Chapter

Optical transmitters convert an input electronic signal into the optical form sent through optical fibers. This task involves both electronics and optics, but this chapter, like the rest of the book, concentrates on the optics. It first introduces the basic operational concepts involved in transmitters, then covers how multiplexing generates signals and modulation converts them to optical form. Finally it looks inside the box to show the functional components of transmitters.

Transmitters contain the light sources described in Chapter 9 and encode signals for the receivers covered in Chapter 11. Chapter 12 covers signal amplifiers and regenerators.

Transmitter Terminology

Strictly speaking, a fiber-optic transmitter is a device that generates an optical signal from an electronic input. An optical transmitter always contains a light source. However, the terminology can get muddled, particularly once transmitters are packaged into commercial equipment, so let's go through a few definitions before getting started.

A *transmitter* generates optical signals; a *receiver* detects them and converts them back into electronic form for equipment at the other end of the system. A *link* is the combination of a transmitter, fiber-optic cable, and a receiver used to send a signal between points. A *data link* is specifically a digital link, usually for computer data transmission, but something merely called a "link" may be digital or analog.

A *system* can be pretty much anything you want it to be. In practice, it usually means the equipment needed to generate an optical signal, transmit it, and receive it. Often this includes the electronics that process input signals to convert them into the form required to drive the light source in the transmitter. Likewise, it often includes electronics, which process the received signals. *Networks* are systems that link many points and contain many transmitters and receivers as well as cables. Later chapters will teach you more

A transmitter generates optical signals from an electronic input. It contains a light source.

A transceiver includes both a transmitter and a receiver that serve one terminal.

about the many different kinds of systems and networks used for telecommunications. A *terminal* is a device attached to a system or network, such as a computer or a phone.

Two-way communications requires that each terminal be equipped with one transmitter and one receiver. It's common to package the transmitter and receiver together in a unit called a *transceiver*, which both transmits and receives signals. Transceivers are also used in many other communication systems. For example, your telephone is a transceiver because it transmits and receives speech; so is the modem that links your computer to the Internet.

If you're familiar with electronics, you'll recognize these terms because they come directly from electronic communications. A broadcast television station has a transmitter; your home television set is a receiver. The television transmitter puts a video signal into the right form for broadcasting; your television receiver converts that signal into a form you can watch. Remember that everything called a transmitter is not fiber optic.

Some of these definitions can be a bit hazy because they depend on packaging, and what the engineers decide to put in the boxes. Although the terms are widely accepted by engineers, sometimes marketing departments have their own ideas. Some are flat-out wrong, like short analog systems called "data links." Others are ambiguous, like "solutions," which can be anything from transmitters to systems.

Operational Considerations

A number of operational considerations shape the design and performance of a fiber-optic transmitter. These include the type of system, the type of modulation, the data rate or bandwidth, the number of optical channels, and optical power requirements.

The higher the transmission speed, the more complex the transmitter.

The higher the system performance, particularly measured as data rate, the more the transmitter has to do and, in general, the more complex it becomes. It's possible to directly modulate the output intensity of an LED by applying an electrical signal across the diode—if the signal is a simple one like analog speech or a slow stream of digital bits. The higher the performance, the more care is needed in modulation. A diode laser needs a bias current in addition to a modulation signal. A high-speed laser in a WDM system needs an external modulator and a thermoelectric cooler to stabilize its operating wavelength. Very high speed circuits also require special electronic circuits able to process the high frequencies involved.

Transmitter and System Packaging

All transmitters include a light source and optical and electronic connections.

Most fiber-optic transmitters are sold as small and fairly simple packages that contain only the essentials for converting electronic signals to optical form. Even the simplest transmitters include a light source and optical and electronic connections. More complex transmitters may include circuits that put the input signal into the proper form for modulation, circuits that drive the light source with the input signal (or with a stable input to generate a steady output), devices to modulate and stabilize temperature, laser output monitors, and external modulators. You will learn more about these functions later in this chapter.

Transmitter modules vary considerably in design. All require some electronic interface for the input signal, and some optical interface to transfer the output signal to an optical fiber. The simplest are little more than an LED built into a connector adapter. Figure 10.1

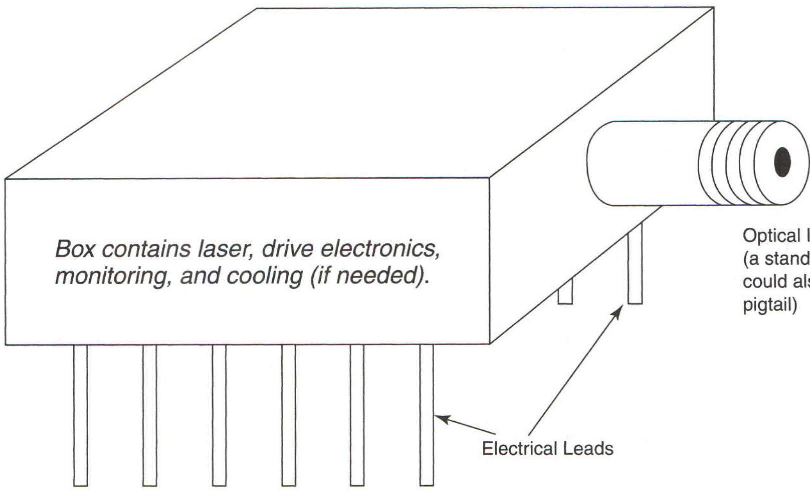


FIGURE 10.1
A simple transmitter module.

shows a more typical module, with a laser source and drive electronics packaged in a small multipin module. Generally a fiber is butted against the light source inside the package, and that fiber delivers the light to the outside world. In a package equipped with a connector adapter, like the module in Figure 10.1, a jumper fiber may deliver the signal to the connector interface; in very simple transmitters, the light source may be built into the connector housing. In either case, a fiber cable mates to the connector interface. Other transmitter modules deliver output via a fiber pigtail, which can be spliced to an output fiber in a patch panel or other splice enclosure.

The industry increasingly uses standardized modules available from a number of vendors in a common format. Figure 10.2 shows a modular Xenpak transceiver. The transmitter portion decodes four input channels encoded in one format, and combines them into a 10-Gbit/s signal encoded in the standard 10-Gigabit Ethernet format that is transmitted out a fiber. Optical, mechanical, and electronic interfaces for the 4.8-by-1.4-by-0.7-inch

Standardized transmitter modules are widely used.

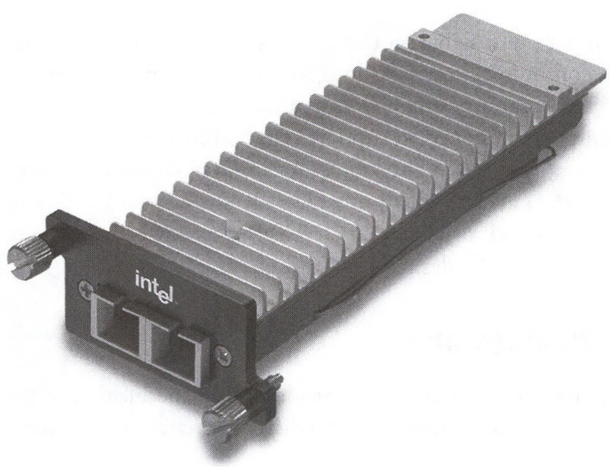


FIGURE 10.2
A Xenpak transceiver for 10-Gigabit Ethernet. (Courtesy of Intel)

package are standard. The module also includes a clock, signal processing circuits, laser control circuits, and a laser driver, as well as a receiver.

These transmitter or transceiver modules typically are built into larger systems, buried inside boxes with only their optical interfaces visible. Larger systems often package transmitter and receiver modules with electronics that perform other functions, such as switching or combining low-speed electronic signals to produce a single higher-speed stream of output data. Although these electronics perform operations on the signals being transmitted, they are more properly considered part of the communication system rather than part of the transmitter.

A WDM transmitter includes a module for each optical channel.

A WDM transmitter is more complex because it contains many light sources operating at different wavelengths, each with its own associated electronics. You can think of a WDM transmitter as an array of transmitters for separate optical channels, each containing a single light source driven by a separate signal at a distinct wavelength. Because our concern is the optics, we'll look at them both as individual single-wavelength transmitters, and as collective multiwavelength transmitters.

Transmitter Performance

The light source or external modulator usually limits transmitter speed.

Electronic and optical components combine to determine the performance of an optical transmitter. The light source or external modulator limits the raw speed and power. No matter what drive electronics you use, you can't make the light signals change faster than the light source (or external modulator) is capable of changing. Likewise, the electronics can't extract more power than the light source is designed to deliver—except, perhaps, in the brief interval between the time the drive power overloads the light source and the moment the light source burns out.

The output wavelength depends mainly on the light source, but also may depend on control circuits that stabilize it at an assigned value. How much stabilization is needed depends on the application. Single-channel systems generally require no wavelength stabilization, but dense-WDM systems need active stabilization to lock the laser at a standard wavelength. Temperature also must be controlled because laser wavelength is temperature-sensitive. Cooling may also be required to limit operating temperature, because laser lifetime decreases as temperature increases.

Transmitter electronics and input signal set the modulation format and clock rate.

The transmitter electronics and the input signal set the optical signal modulation format and data rate (called *clock rate* in communications). As long as the laser or external modulator can handle the speed and power, it can transmit any format the electronics can support. Normally the transmitter electronics are designed to support standard formats.

Electronics also monitor the operation of the light source. An internal sensor may monitor output power from the rear facet of a laser, which usually transmits a small fraction of light for this purpose. Other circuits check drive-current levels, important because aging lasers need more drive current to generate the desired power level.

Analog and Digital Transmission

Optical transmitters can generate digital or analog signals.

Light sources are inherently analog devices, with output proportional to the modulating signal. An analog modulation circuit generates analog signals; a digital driver generates digital pulses.

Chapter 3 introduced analog and digital transmission. Recall that each has its virtues. Our eyes and ears are analog devices, so audio and video signals have to start and end in analog format. On the other hand, analog signals require much more precise reproduction and transmission than digital signals. This makes analog signals far more vulnerable to noise and distortion during transmission and processing. Digital signals can better tolerate distortion because they usually need only to detect whether a binary signal is off or on, not its shape or level. (Multilevel digital codes exist, but so far their only uses in fiber optics have been in the laboratory.) Digital electronics also are easier to design and cheaper to buy.

Digital transmission demands faster response than analog signals carrying the same information. Earlier you learned that a single telephone voice line requires only 3000 Hz of analog bandwidth, but needs 64,000 bits per second of digital transmission capacity. The two signals carry the same information. The digital version contains frequencies much higher than the 3000 Hz analog signal, but the digital signal does not have to be reproduced with the exacting precision needed for analog signals. The edges of digital pulses can be blurred as long as the receiver can tell the difference between on and off, but analog distortion is noise.

Digital signals are more robust than analog.

Although digital signals are far more common than analog in modern communication systems, some analog optical transmitters remain. As you will learn later, their most important applications are in cable television systems.

Bandwidth and Data Rate

Transmission speeds are measured as bandwidth in analog systems and data rate or bit rate for digital systems. Analog bandwidth normally is defined as the frequency where the amplitude of the modulated signal drops 3 dB below the value at low frequencies, a 50% reduction in power. The digital data rate is the number of bits per second that can be transmitted with no more than a specified fraction of errors, often one incorrect bit in every trillion bits (10^{12}).

Frequency bandwidth measures analog capacity. Bit rate measures digital capacity.

Both of these are quantities measured at the receiver, and don't directly measure the response or *rise time* that limits transmitters. Rise time is defined as the interval it takes light to rise from 10% to 90% of the steady-state high power level. *Fall time* is the inverse, the delay needed for the signal to drop from 90% to 10% of the maximum. If the rise and fall times are equal (they aren't always), this can be used to approximate bandwidth,

Rise time limits transmitter speed.

$$\text{Bandwidth (MHz)} = \frac{350}{\text{rise time (ns)}}$$

The precise relationship between bandwidth and rise time differs among light sources and transmitters.

Rise time is an important variable in selecting light sources and modulation techniques. LEDs have rise times ranging from a few nanoseconds to a few hundred nanoseconds. Directly modulated diode lasers have much faster rise times than LEDs (typically a fraction of a nanosecond), with VCSELs faster than edge-emitting diode lasers. In practice, edge-emitters can be directly modulated at rates to 2.5 Gbit/s, and VCSELs can reach 10 Gbit/s.

As you learned in Chapter 9, direct modulation induces a chirp in wavelength that can contribute to dispersion in long-distance transmission. Direct modulation normally is not used at speeds above 2.5 Gbit/s in long-distance systems, as external modulation usually is used at higher rates. Direct modulation can be used in short 10-Gbit/s systems, but external modulation is necessary at 40 Gbit/s.

Multiplexing

As you've seen earlier, multiplexing is the combining of multiple signals into a single entity that can be transmitted more economically. Multiplexing takes place at or before the transmitter. There are three important types, and their handling at the transmitter differs.

Time-Division Multiplexing

Time-division multiplexing interleaves bits from data streams to form a faster signal.

Traditional time-division multiplexing (TDM) combines two or more digital signals by interleaving bits or bytes from separate data streams to give one faster signal, as shown in Figure 10.3. For example, 24 voice phone lines, digitized at 64,000 bits per second, can be combined into one 1.55-Mbit/s digital signal. The combined signal carries all the bits from the 24 digitized phone signals, plus extra bits that help organize the combined signals. Appendix C lists the standardized hierarchy of successively higher data rates developed for telecommunication systems.

Alternatively, incoming streams of data can be broken into groups of bits called *packets*, which are transmitted together rather than interleaved with bits from other data streams. Incoming packets are held in an electronic buffer until they can be transmitted. This technique, used on the Internet, is sometimes called *statistical time-division multiplexing* to distinguish it from the traditional interleaving of bits shown in Figure 10.3. You'll learn more about the differences in Chapter 19.

In current systems, signals are time-division multiplexed by electronic circuits before they reach the transmitter. The electronic multiplexers that combine slower bit streams to make a higher-data-rate signal may be in the same box or rack as the transmitter. The higher the multiplexed data rate, the more important it is to perform electronic multiplexing close to the transmitter, because of problems with high-speed electronic transmission. Care must be taken in laying out electronic components inside transmitters operating at 10 Gbit/s or above. At the present time, the highest time-division multiplexing rate in regular use is 10 Gbit/s. Externally modulated transmitters have been developed for 40 Gbit/s, but there is little demand for that extra capacity.

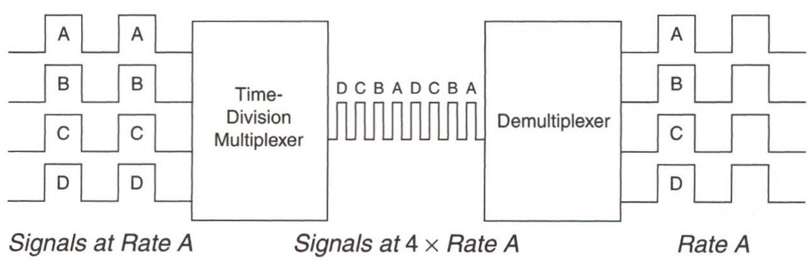


FIGURE 10.3 *Time-division multiplexing.*

Electronic time-division multiplexing becomes extremely difficult at higher data rates. An alternative is *optical time-division multiplexing*. Interleaved optical TDM has been demonstrated in the laboratory, but applications are far off.

Frequency-Division Multiplexing

Frequency-division multiplexing combines two or more signals modulated on carriers at different frequencies to produce one signal covering a range of frequencies. This system is used in broadcast radio and television and in cable television. Traditionally frequency-division multiplexing is used for analog signals, but it also can be used for digital signals.

Frequency-division multiplexing combines signals at different frequencies.

Frequency-division multiplexing divides a range of frequencies into a set of distinct channels with fixed bandwidths that do not overlap. Each input signal modulates the carrier frequency for one channel, producing a signal that fits into one channel slot. Combining the modulated carriers produces a signal that spreads across a wider range of frequencies. You can see this on an AM or FM radio dial, where each station has a nominal frequency (the carrier) that actually spreads across a wider range, but should not overlap with the signals of other stations. The radio band contains dozens of stations; you tune your receiver to select a specific station. Television works the same way, but the channels are numbered rather than named by frequency, and some frequencies are reserved for services other than television.

Cable television also uses frequency-division multiplexing, but transmits the combined signals through optical fiber and coaxial cable rather than broadcasting them. Like broadcast television, cable systems assign channel numbers, which identify assigned frequencies. The different channels may carry different types of signals, including analog video, digital video, voice, and data.

Like time-division multiplexing, frequency-division multiplexing is done electronically before the signal reaches the transmitter. In practice, the term *frequency-division* is limited to multiplexing at radio frequencies.

Wavelength-Division Multiplexing

Think of wavelength-division multiplexing as being the optical version of frequency-division multiplexing. It transmits multiple optical signals through the same optical fiber at different wavelengths, just as frequency-division multiplexing transmits multiple radio signals at different frequencies. The basic principles are the same, but the terminology and details are different.

Wavelength-division multiplexing is the optical version of frequency-division multiplexing.

In practice, one optical transmitter is assigned per wavelength, as shown in Figure 10.4. The input is (generally) a digital signal from an electronic multiplexer. The optical transmitter modulates that signal onto the output of a light source at a wavelength λ. Other signals modulate the outputs of other transmitters with light sources at other wavelengths.

Separate fibers deliver the output of each transmitter to an optical multiplexer, which combines them for transmission through a single output fiber. Each wavelength in the signal is a separate optical channel, which if the system is designed properly does not affect other optical channels, as in frequency-division multiplexing of radio broadcast through the air.

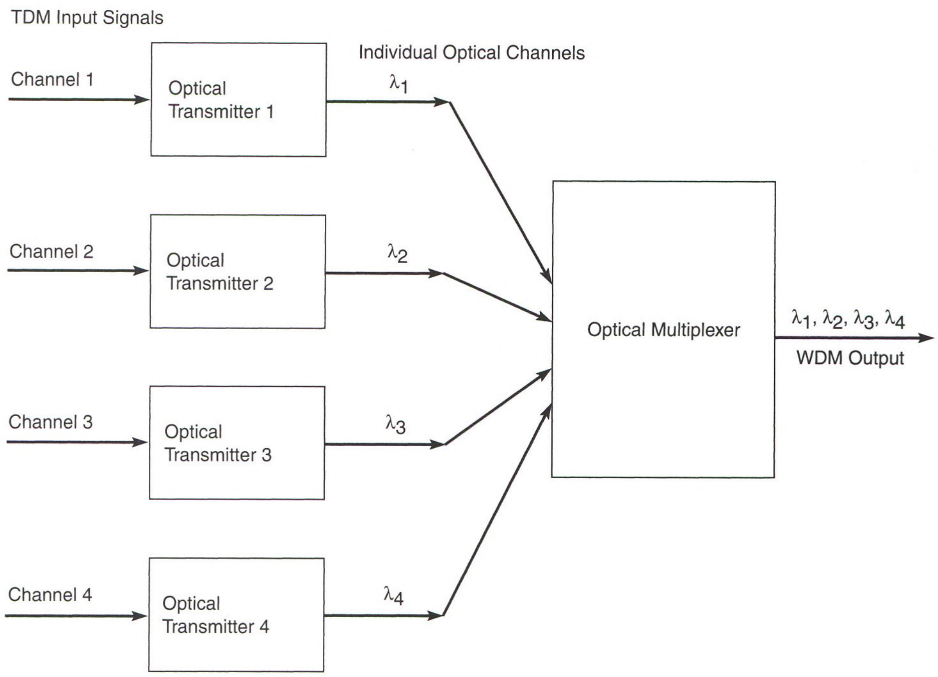


FIGURE 10.4 *Wavelength-division multiplexing at the transmitter.*

Wavelength-division multiplexing comes after the light source.

Note that wavelength-division multiplexing takes place *after* optical transmitters generate modulated optical signals at different wavelengths. Time-division and frequency-division multiplexing are both done electronically, *before* the signals modulate a transmitter.

Later chapters will cover other aspects of wavelength-division multiplexing in more detail, particularly its implications in overall system design and performance.

Modulation

So far, we have discussed modulation in very general terms. Transmitter performance depends strongly on how the light source is modulated, so let's take a look at the details.

Amplitude or Intensity Modulation

Most optical carrier signals are modulated in intensity.

Most optical transmitters are modulated by signals that change the amplitude or intensity of the light they generate. Figure 10.5 shows how this works for an ideal light source that normally generates a steady coherent light wave.

The ideal light wave at the top is the *carrier signal*, like the carrier frequency of a broadcast radio or television station. *Amplitude modulation* changes the amplitude or intensity of the output light as the amplitude of the drive signal changes. This is a straightforward approach because the output power of an LED or diode laser increases with drive current.

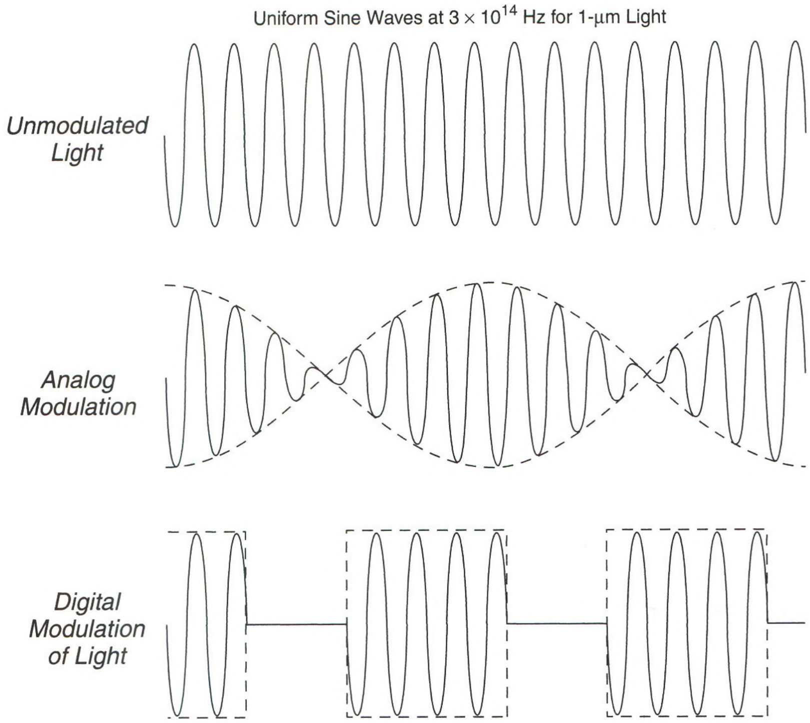


FIGURE 10.5 *Amplitude modulation by digital and analog signals.*

This can produce the analog signal at the middle of Figure 10.5 or the digital signal at the bottom.

The figure was distorted in one important way to show the scale of the modulation. Light at 1500 nm has a frequency of about 200 THz, or 10^{14} Hz. The signals modulating the light wave are at much lower frequencies, measured in gigabits per second for a digital signal. If the figure was drawn to scale, one pulse from a 10-Gbit/s data stream would contain around 20,000 waves of light. That's impossible to draw, so the figure pretends the optical and modulation frequencies are much closer.

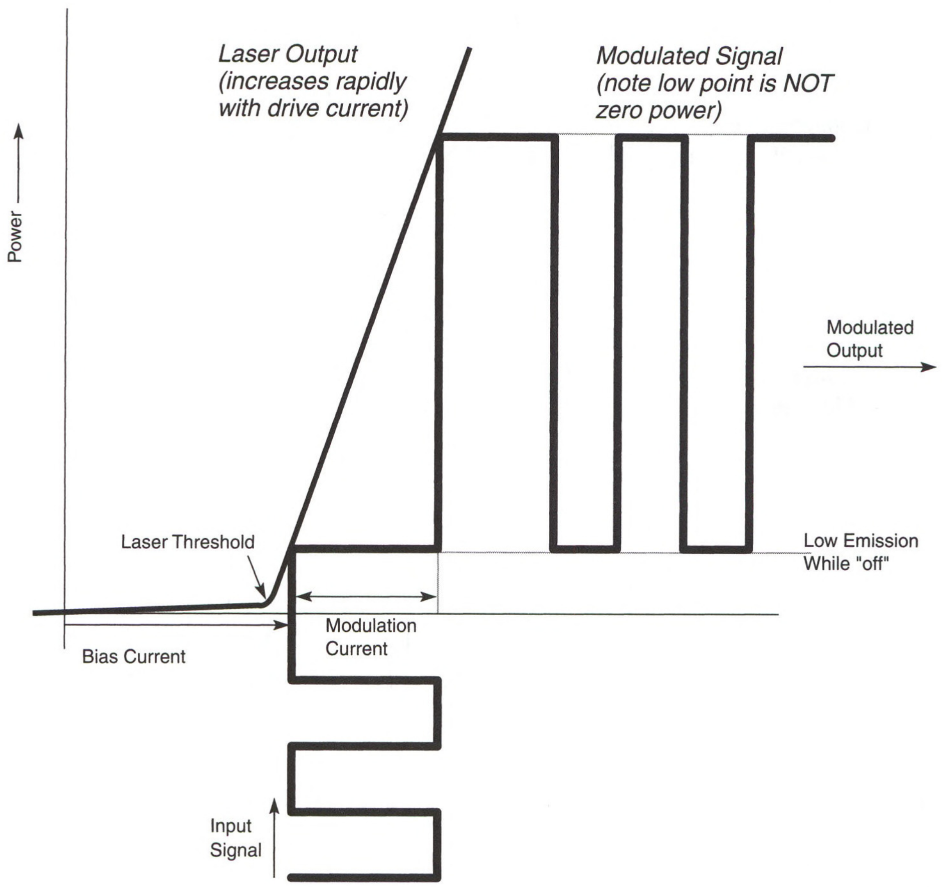
Amplitude modulation is standard in fiber-optic systems because it's simple and easy. Light source output naturally varies with drive current, and intensity modulators are relatively easy to build.

Direct and External Modulation

As you've learned, semiconductor light sources can be modulated either directly or externally. Increasing the drive current increases the power emitted by either LEDs or semiconductor lasers. Diode lasers respond very quickly to the increase, but LEDs have slower response, limiting their modulation bandwidths.

Direct modulation is ideal for inexpensive transmitters, but it causes an undesirable wavelength chirp, which causes excessive chromatic dispersion at high speeds. In addition, lasers develop undesirable relaxation oscillations at frequencies of a few gigahertz, which limits the

FIGURE 10.6
Direct modulation of a laser diode.



maximum frequency for direct modulation. External modulators are needed at higher speeds, or when the light source cannot be directly modulated. They are covered in Chapter 16.

Lasers are modulated by adding a signal current to a steady bias current.

LEDs normally are switched off and on because they turn on as soon as the current starts. The threshold effect complicates the operation of diode lasers. When a diode laser is switched on, emission does not begin until the drive current exceeds the threshold, delaying the output pulse. This can be a problem at high speeds, where delay can significantly shorten the pulse. To prevent this effect, diode lasers normally have two sources of drive current, which add together. One produces a steady bias current, which typically slightly exceeds laser threshold. The other is the time-varying signal, which actually modulates the laser output by increasing the current above the bias level, as shown in Figure 10.6.

This bias arrangement leaves the laser emitting some light when it is nominally "off," but much more when it is "on." Receivers can accommodate this difference by setting proper decision thresholds for the presence or absence of pulses, as you will learn in Chapter 11.

Don't forget that semiconductor diodes respond differently to current than to voltage. As you saw in Chapter 9, a minimum voltage has to be applied across an LED or laser to give the charges carrying current through the device enough energy to recombine at the junction level. Once that *voltage* is exceeded, current starts flowing. That current is enough to start an LED to emit some light, but the drive current must exceed a threshold to produce stimulated emission from a diode laser.

Coherent Transmission

If you're familiar with radio, you know that amplitude modulation is not particularly sophisticated. The amplitude-modulated AM-radio band is justly notorious for its static and background noise. Modulating the frequency of the carrier signal rather than the amplitude gives the FM (frequency-modulated) radio band much better signal quality. AM receivers pick up random spikes of amplitude noise from spark plugs and power lines, and the signal strength fades with distance from the receiver. In contrast, FM receivers do not pick up random noise spikes because they don't change the frequency of the radio signal. In addition, the strength of an FM signal depends not on its intensity but on how it changes the carrier frequency, so signals don't fade into the background; they stay strong until they start breaking up. (Other differences in AM and FM reception come from the different transmission frequencies.)

You might think it logical to try frequency modulation to improve optical transmission. In fact, it's been tried, but hasn't worked out very well.

Frequency modulation is one type of what optical engineers call *coherent transmission*, which works like a heterodyne (FM) radio system. The trick is to combine the incoming frequency-modulated signal with another signal kept at a constant frequency. Processing the difference between the input signal and the constant frequency (called a local oscillator) reproduces the radio program. As shown in Figure 10.7, the optical version requires a pair of lasers, one at the transmitter and a second (the local oscillator) at the receiver. The two lasers emit slightly different frequencies, v_1 and v_2. The transmitter modulates the frequency of the outgoing laser beam by passing it through a suitable external modulator. Alternatively, a modulator could delay the phase of the transmitter beam, causing a phase shift. At the receiver, the incoming signal at the transmitter frequency is mixed with the local oscillator beam, to give a microwave signal at the difference between the frequencies of the two light waves. That microwave signal carries the frequency- or phase-modulated signal, which can be extracted by further processing.

Coherent optical transmission works like an FM-band radio, but has not yet proved practical.

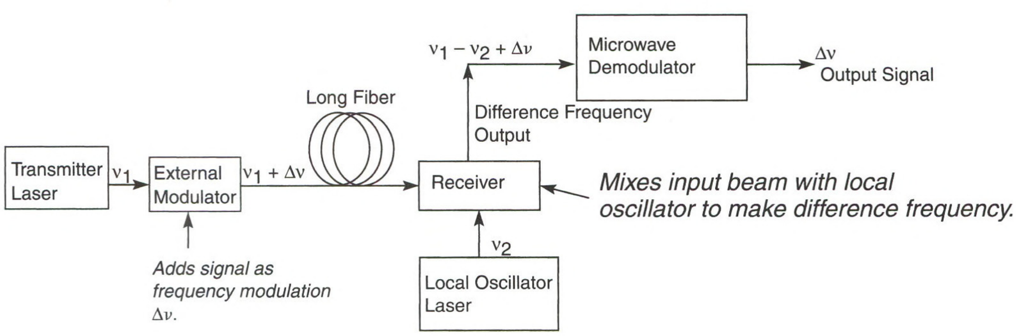


FIGURE 10.7
Coherent optical transmission.

Experiments have shown that coherent transmission can work, but so far it has not proven practical, and it's largely been forgotten in the explosive development of wavelength-division multiplexing and optical networking.

Single-Channel Transmitter Design

We've already covered several components of optical transmitters. To pull the whole picture together, we'll now consider a generalized single-channel transmitter as a whole. Our example will include the elements needed in high-performance laser transmitters (some won't be present in low-speed LED transmitters). To keep the picture clear, we assume the transmitter receives its input signal in final electronic form from an external source, and doesn't have to encode any signals. This type of transmitter is usually a module inside a larger system. For convenience, we assume the wavelength is fixed, not tunable.

You should remember that the real world is more complex. For example, a transmitter and a receiver are often packaged together as a transceiver; pairs of transceivers are attached to opposite ends of a fiber pair for two-way transmission; transmitters operating at separate wavelengths may be packaged together if their outputs are directed into the same fiber; sometimes some signal encoding is done inside a transmitter module; tunable lasers are starting to come into use; and sometimes a transmitter may be packaged with other equipment in a larger box that is also called a "transmitter," although it may also perform other electronic and optical functions.

Figure 10.8 is a functional diagram of a transmitter module. (You'll learn about receivers in Chapter 11.) Its main functional elements are:

- Housing
- Electronic interfaces

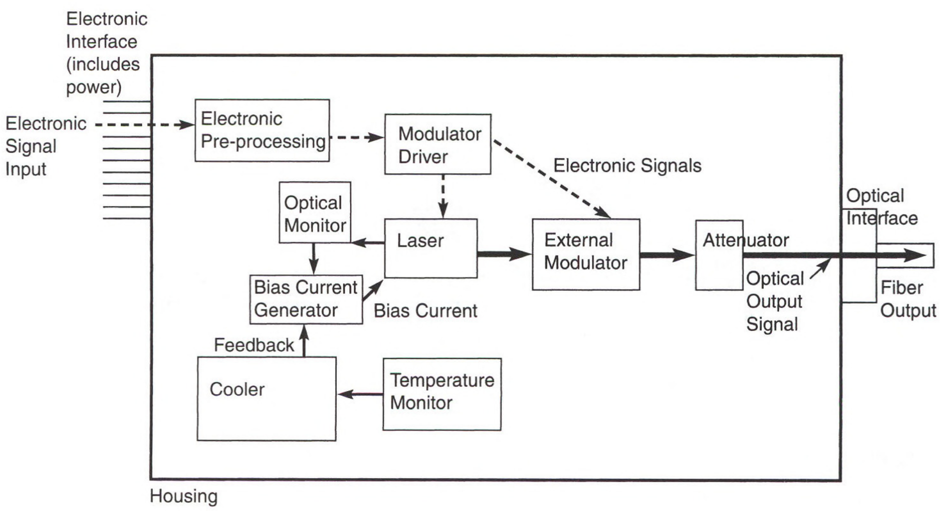


FIGURE 10.8 *Generic optical transmitter.*

- Internal signal-processing electronics
- Laser monitoring and bias circuits
- Temperature control
- Optics (including laser and external modulator)
- Optical interfaces

Some control functions can be performed by circuits outside the packaged transmitter. For example, output of the sensor that monitors laser output can be routed to external circuits that adjust bias current. Temperature data also can be routed to external controls. Here we will consider their functions rather than their locations.

Housing and Electronic Interfaces

The mechanical housing of an optical transmitter is a box designed to mount conveniently within other equipment. Screws, solder bonds, or other fasteners attach the housing mechanically to a printed circuit board or other substrate. More complex transmitters are packaged in cases that mount in standard equipment racks.

The mechanical housing is designed to mount conveniently in other equipment.

Typically, pins on the package provide electronic connections with other devices. They deliver power to drive the laser, the input signal, and other required signals. The transmitter also may return some information to other equipment, such as transmitter status.

Signal Processing Electronics

Internal electronics typically do some processing of the input signal to put it into a form suitable for modulating the light sources. One function is converting signals from the voltage variations used in electronic circuits to the current variations needed to directly modulate diode lasers and LEDs. Other processing may change signals to formats better suited for fiber transmission. Transmitters used in some networks may include buffers to hold input data until it can be sent, because the networks can deliver data faster than the transmitter can send the data.

Internal electronics put the input signal into a form suitable for modulating the light source.

Figure 10.8 shows the path of the signal from the outside connection through the electronic preprocessor, and modulator driver to either the diode laser or the external modulator. In direct-modulation systems, the modulation current is added to the bias current to drive changes in the optical output.

Laser Drive and Monitoring Circuits

The handling of laser drive, bias, and monitoring circuits depends on the type of modulation.

For direct modulation, a bias circuit provides the bias current that drives the laser to a point just above threshold so it generates a weak beam. A separate drive circuit adds the modulating current, which for digital transmission is a series of pulses. When the pulses are "on," the laser output is high.

For external modulation, a bias circuit drives the laser so it emits a steady output power high enough to compensate for any losses in the external modulator. A separate drive circuit delivers the signal to the external modulator, causing it to vary from opaque to transparent and switch the beam off and on.

In both types of laser transmitter, some light from the laser is directed to a sensor that monitors the laser output. Typically this is a small amount of light coupled out the back of the laser, but it could be a small part of the output beam. The sensor measures the intensity of this light and uses that information to drive a feedback circuit, which adjusts the bias current to keep the output power steady. Laser power declines as the laser ages, so this feedback circuit turns up the bias current to compensate for this decline in power. (Eventually, however, the laser will no longer be able to meet power specifications.)

Temperature Control

Temperature stabilization maintains a fixed wavelength.

The threshold current, output power, and wavelength of a diode laser vary with its operating temperature, making temperature stabilization important in high-speed or narrow-line transmitters.

Power and threshold current variations are important in determining laser lifetime. The threshold current, I_{thresh}, increases exponentially with temperature T:

$$I_{\text{thresh}}(T) = I_0 e^{(T/T_0)}$$

where I_0 is a constant and T_0 is the characteristic temperature of the laser material. Simple double-heterostructure InGaAsP lasers have T_0 of 50° to 70°K, but strained layer structures, quantum wells, and improved confinement can increase T_0 values to as high as 180°K. The characteristic temperature is higher for GaAs lasers of comparable structures; for simple lasers, T_0 is 120°K. Increasing the temperature reduces the slope efficiency of light generation above laser threshold, further decreasing overall efficiency and output power produced at a particular drive current. Reduced efficiency increases heat generation, which warms the laser and, without adequate heat dissipation, can lead to thermal runaway.

Wavelength variations are particularly important for lasers used in dense wavelength-division multiplexing, where the wavelength must be kept constant within a small fraction of a nanometer to keep the signal in the desired optical channel. The temperature affects both the refractive index of the semiconductor and the physical length of the cavity, two factors that determine the output wavelength. Details vary with the material and laser structure, but in general changing the temperature of a laser by 10°C changes the wavelength about 1 nm. Therefore, a change of just a few degrees can shift the laser's output to the adjacent channel in a dense-WDM system.

Wavelength-insensitive transmitters can operate uncooled at 10 Gbit/s.

Cooling requirements depend on the system. Heat sinks and passive cooling can suffice for data rates to 10 Gbit/s if the output power is not high and if the system design allows the laser wavelength to vary by 20 nm. In practice, that variation is allowable in single-channel systems transmitting through standard single-mode fiber at its zero-dispersion wavelength of 1310 nm. Heat sinks also might be used in WDM systems with widely spaced wavelengths. But in practice there is little interest in uncooled operation in the 1550-nm window, because most systems operating in that band use closely spaced WDM channels. In such cases, wavelength tolerances are tight, output powers are high, or the system is very sensitive to wavelength chirp and dispersion, so active cooling is required.

Active cooling normally uses a temperature monitor to control a thermoelectric cooler, which can maintain transmitter tolerance within the required range.

Optics and Optical Interfaces

The optical part of the transmitter starts with the laser, which generates either a steady beam or a modulated output depending on the input. Monitoring the laser's output through the rear facet controls the laser's output power through feedback to the bias-current generator.

Modulation either adds to or subtracts from the light generated by the laser source. If the laser is directly modulated, the modulation drive current increases the laser's output power above the biased level where it emits a little light. If the laser is modulated externally, the bias current drives it at a high level, and the modulator varies between fully transparent and essentially opaque. That means the external modulator *reduces* the power level in the laser beam. As with direct modulation, a small amount of power may be transmitted in the "off" state.

Direct modulation adds to the laser output from a low-bias current.

An attenuator is optional. It may be needed if the receiver is close to the transmitter, and might be overloaded by the transmitter's unattenuated power. Attenuators are most likely to be used in networks that use standard transmitters, but where the attenuation in the cable can vary over a wide range.

Wavelength Tunability

Including tunable-wavelength lasers will increase transmitter complexity. In addition to monitoring temperature and power, the transmitter will need to monitor and stabilize the operating wavelength within system margins. Many applications also will require the operator to adjust laser wavelength manually or remotely, either so tunable lasers can be used as replacements, or so the transmitter can be reconfigured. Few tunable lasers are now used in transmitters, so we won't worry about the details.

Sample Transmitters

The best way to get a feeling for the internal workings of transmitters is to look at examples, deliberately simplified to aid in understanding basic concepts.

Figure 10.9 shows a very simple drive circuit for an LED. A bias voltage $+V$ is applied across a transistor, LED, and current-limiting resistor, going to ground. This provides the

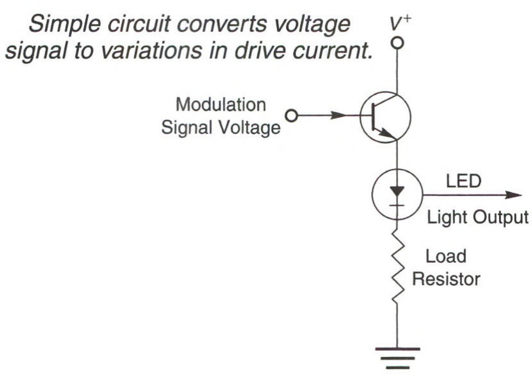


FIGURE 10.9
Simplified drive circuit for LED.

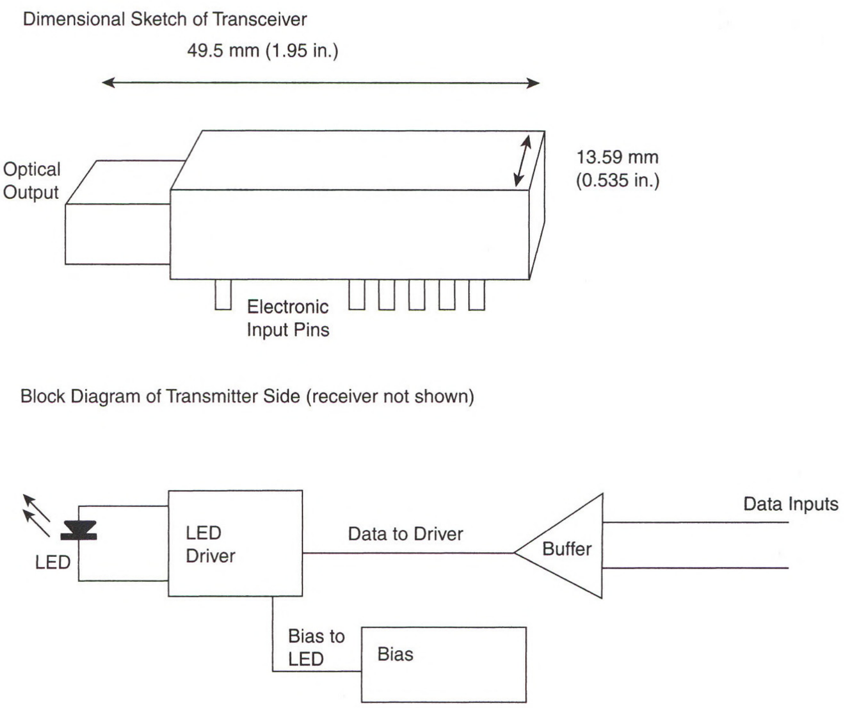


FIGURE 10.10 *156-Mbit/s fiber-optic transceiver, packaged with integral small-form-factor connector.*

forward-voltage bias needed by the LED (about 1.5 V for 850-nm emitters and around 1 V for 1300-nm LEDs). The input signal is delivered as a modulated voltage applied to the base of the transistor, which causes variations in the current passing through the LED and load resistor. The LED could be on either side of the transistor, but the circuit requires a transistor or other circuit element to modulate the drive current. The resistor limits LED current. The circuits that generate the input signal are not shown. The higher the speed and performance level, the more complex the circuit.

These transmitters can be made compact. Figure 10.10 shows the dimensional outlines of a transceiver, which includes a 1300-nm LED transmitter able to operate at speeds to 156 Mbit/s. The figure also shows a block diagram of the transmitter portion. The whole integrated package (transmitter and receiver) is just under 50 mm (2 in.) long, including a built-in connector interface at the left. (One thing to watch out for is that some mechanical specification sheets still don't label the units of dimensions. They usually include both inches and millimeters, with the metric units the higher numbers, but they may not label them. Remember what happened to Mars Climate Orbiter when a NASA contractor forgot to label units!)

Diode lasers have electrical characteristics similar to those of LEDs, but their optical operation differs. Lasers emit little light until drive current passes a threshold value, but above that threshold tend to emit higher power with more efficiency. Lasers draw much higher drive currents than LEDs, so they normally are used with smaller current-limiting resistors. Laser transmitters also may require additional components to meet the more demanding requirements of laser operation, including a sensor to monitor laser output, a temperature-sensing

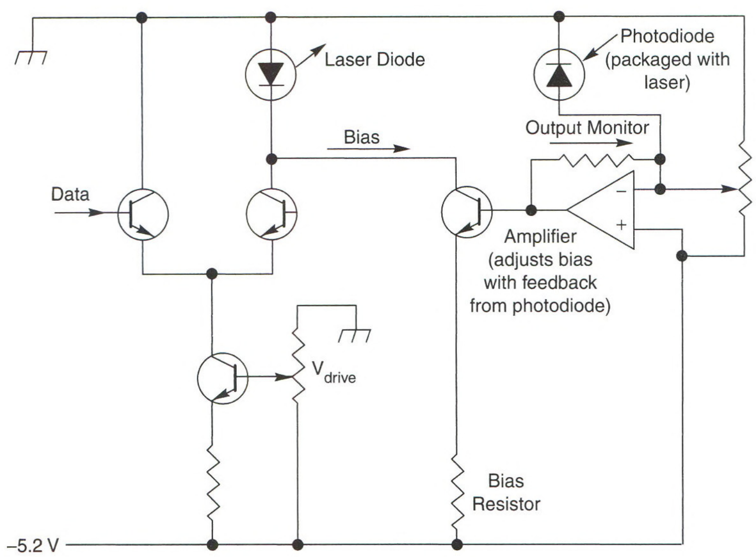


FIGURE 10.11 *Laser diode drive circuitry. (Adapted with permission from a figure by Paul Shumate)*

thermistor to monitor transmitter temperature, and a thermoelectric cooler. Typical laser transmitters are somewhat larger than the one shown in Figure 10.10, to accommodate these extra components.

The circuit in Figure 10.11 is an example of the type used in a directly modulated laser transmitter. The drive signal is applied as a voltage to the base of a transistor, where it adds to a bias voltage and modulates drive current through the laser diode. The detector packaged with the laser monitors its output, providing feedback to an amplifier (at right), which adjusts the bias applied to the laser diode so average power remains constant. Externally modulated lasers require simpler drive circuits because they need only provide constant output power, but the transmitter then requires drivers for the external modulator.

Externally modulated lasers have simpler drive circuits, but the transmitters require separate electronics to drive the external modulator.

Typically the drive circuit prebiases the laser with a current close to threshold. Adding the modulated drive signal raises it above the threshold, so it starts emitting light. This approach enhances speed by avoiding the delay needed to raise the drive current above threshold. At low speeds, the prebias may be below the threshold, to avoid generating low-level emission that might confuse the receiver. At higher speeds, the laser may be prebiased to emit a little light in the off state, with addition of the modulated drive signal increasing power greatly. Prebiasing requires careful adjustments so the receiver does not mistake the low emission from the laser in its off state for a faint pulse in the on state.

Steady advances in electronic packaging and integration have squeezed high-performance transmitters into quite compact packages. Figure 10.12 shows an XFP transceiver module along with a functional diagram. An entire 10-Gbit/s laser transmitter and receiver fit into a case that measures 78 mm long, 18.4 mm wide, and 8.5 mm high. It operates on 3.3 volts and draws 1 to 2 watts of electrical power. It operates uncooled, generating up to a milliwatt of light from a 1310-nm laser source. Optical interfaces are in the front—a pair of standard LC fiber connectors, one for the input and the other for the output. The electrical interface is a 30-pin electrical connector in the back.

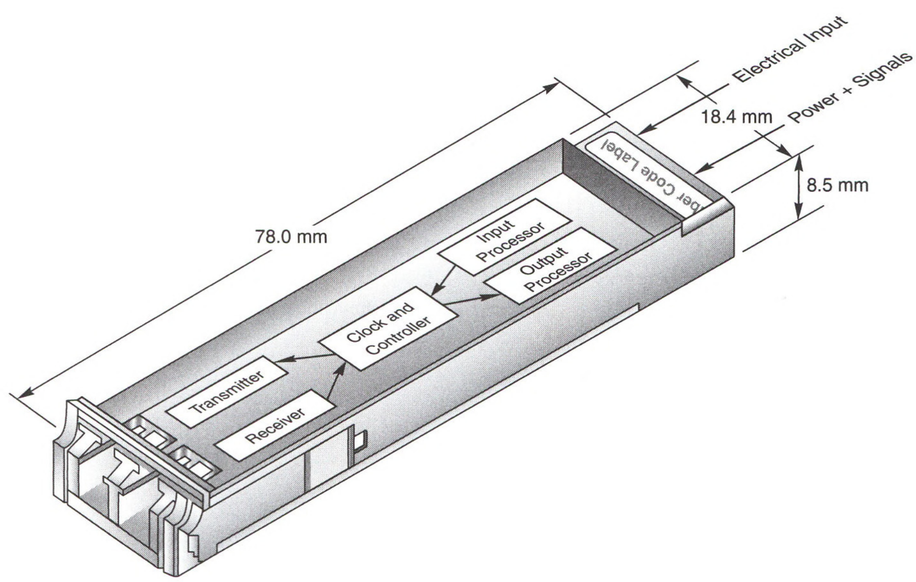


FIGURE 10.12
An XFP transceiver with a block diagram of its components.

The XFP is one of several standardized modules developed for 10-Gbit/s transmission and offered by multiple developers. The design reflects a growing trend in the communications industry of standardizing mass-produced, interchangeable modules. The modules differ somewhat in design philosophy. The XFP module is particularly small because it includes only the minimal electronics needed to drive the transmitter at 9.95 to 11.1 Gbit/s, as shown in the block diagram of Figure 10.8. Other standard modules such as Xenpak include electronics that format input signals for transmission standards such as 10-Gigabit Ethernet. That approach requires extra circuits, so those modules must be larger.

What Have You Learned?

1. A transmitter contains a light source and generates optical signals from an electronic input. It includes optical and electronic connections.
2. A transceiver is a package that includes both the transmitter and receiver on one end of a system. It connects to a pair of fibers.
3. Transmitters range from simple to complex. The complexity increases with transmission speed.
4. Wavelength-division multiplexing requires a transmitter module for each optical channel that generates a separate wavelength.
5. Transmitter electronics and the input signal define the modulation format and the clock rate for a transmitter.
6. Optical transmitters may generate digital or analog signals. Digital signals are more robust than analog, but require higher data rates to carry the same information.

7. Frequency bandwidth is the capacity of an analog transmitter. Data rate is the capacity of a digital transmitter. Both depend on the rise time of the transmitter.
8. Time-division multiplexing combines bits from data streams to form a faster signal. Frequency-division multiplexing assigns signals to different frequencies combined into one signal. Both are done electronically before the signal is fed to the optical transmitter.
9. Wavelength-division multiplexing transmits separate signals through one fiber at many different wavelengths. It requires one transmitter per optical channel. The signals are combined on the fiber after the optical transmitter.
10. Optical carrier signals are modulated in intensity.
11. Major elements of a typical transmitter are the housing, the electronic interfaces, the internal signal-processing electronics, the detector and circuits to monitor laser bias, temperature control, the laser and (optional) external modulator, and the optical interfaces.
12. Temperature stabilization is important in maintaining stable wavelength and output power from the laser.

What's Next?

Now that you have learned about fiber-optic transmitters, Chapter 11 will examine the other end of the system, the receiver.

Further Reading

HP Fiber Optic Technical Training Manual, available from *http://www.agilent.com/*

Paul W. Shumate, "Lightwave Transmitters," in Stewart E. Miller and Ivan P. Kaminow, eds., *Optical Fiber Telecommunications II* (Academic Press, 1988)

Questions to Think About

1. The difference between the "off" and "on" states of a laser transmitter is 20 dB. The "on" output is 1 mW. What is the "off" output at the output port of the transmitter? What is the "off" output after 30 dB of loss?
2. The diode laser used in a transmitter has a threshold current of 10 mA and normally operates at 15 mA in the "on" state. Suppose it is directly modulated with a signal without a bias current, which turns the laser on from zero current. The signal pulse has 30-ps rise time, 30-ps "on" time, and 30-ps fall time. How long is the output optical pulse, starting from the time the current crosses laser threshold?
3. Suppose you could find electronics fast enough to generate time-division multiplexed signals at 640 Gbit/s on a single optical channel. How many light waves would one bit correspond to at a wavelength of 1550 nm?

4. Time-division multiplexing requires reducing the duration of low-speed pulses and interleaving them into a combined signal. It now is done electronically. Suppose you had a way to reduce the duration of optical pulses. Can you think of a way to interleave these shortened optical pulses for time-division multiplexing? Consider a system that multiplies data rate by a factor of four. (*Hint:* Think about ways to delay pulses.)

Chapter Quiz

1. Digital transmission capacity is measured as
   a. bandwidth in megahertz.
   b. rise time in microseconds.
   c. frequency of 3-dB point.
   d. number of bits transmitted per second.
2. Analog transmission capacity is measured as
   a. bandwidth in megahertz.
   b. rise time in microseconds.
   c. frequency of 3-dB point.
   d. number of bits transmitted per second.
3. If the rise time of a transmitter is 1 ns, what is its theoretical bandwidth?
   a. 1 Gbit/s
   b. 100 MHz
   c. 350 MHz
   d. 350 kHz
   e. 350 Mbit/s
4. Standard optical interfaces for transmitters are
   a. integral optical connectors or fiber pigtails.
   b. integral electronic connectors or fiber pigtails.
   c. output windows or fiber pigtails.
   d. 14-pin DIP packages.
   e. only fiber pigtails.
5. How many transmitters are needed for wavelength-division multiplexing?
   a. none; the signals are combined in the optical fiber
   b. one
   c. one per optical channel
   d. depends on the data rate per channel
6. What provides feedback to stabilize laser intensity in a transmitter?
   a. a signal relayed from the receiver
   b. changes in input impedance

c. output from the rear facet of the laser monitored by a photodiode
d. light scattered from the optical interface with the input fiber
e. no feedback is required

7. What is the usual modulation method for fiber-optic transmitters?
a. intensity modulation
b. frequency modulation
c. wavelength modulation
d. voltage modulation

8. What does time-division multiplexing do?
a. transmits different signals at different wavelengths
b. shifts the frequencies of several analog signals to combine them into a single input
c. encrypts signals for secure transmission
d. interleaves several digital signals into a single data stream

9. What is the total data rate of a WDM system carrying 2.5-Gbit/s signals at 1550, 1552, 1554, 1556, 1558, 1560, 1562, and 1564 nm?
a. 2.5 Gbit/s
b. 10 Gbit/s
c. 12.5 Gbit/s
d. 20 Gbit/s
e. 25 Gbit/s

10. With wavelength-division multiplexing, how many fibers do you need for two-way transmission of 2.5-Gbit/s signals at 1550, 1552, 1554, 1556, 1558, 1560, 1562, and 1564 nm?
a. one
b. two
c. four
d. eight
e. sixteen

11. A 1300-nm LED-based transmitter has rise time and fall time of 1.2 nanoseconds. What is the best application?
a. transmitting 10 Gbit/s through single-mode fiber
b. transmitting Gigabit Ethernet (1 Gbit/s data rate) through graded-index multimode fiber
c. transmitting fast Ethernet (100 Mbit/s data rate) through graded-index fiber
d. transmitting ATM signals (155 Mbit/s data rate) through single-mode fiber
e. transmitting 1.5 Mbit/s through graded-index fiber

12. The LED-based transmitter in Question 11 has minimum output of −19 dBm into 62.5/125 graded-index multimode fiber. The receiver requires an input of at least −30 dBm. If fiber attenuation is 2 dB/km and other losses total 3 dB, how far away can you put the receiver?

a. 1 km

b. 3 km

c. 4 km

d. 8 km

e. 11 km

13. How is LED output modulated?

a. externally by varying current delivered to an external modulator

b. directly by varying drive current

c. directly by varying voltage applied to an external modulator

d. directly by varying LED operating temperature

14. Temperature stabilization of a laser transmitter also stabilizes what operating characteristics?

a. laser threshold

b. output power

c. wavelength

d. all of the above

e. none of the above