CHAPTER

14

Couplers and Other Passive Components

About This Chapter

A variety of components manipulate optical signals in fiber-optic systems. They fall into two broad categories: *passive components* that require no outside power supply, and *active components* that draw external power. This chapter covers couplers and other passive components that are not involved in wavelength-division multiplexing. Chapter 15 covers WDM optics including couplers, and Chapter 16 covers switches, modulators, and other active components.

Couplers split input signals into two or more outputs, or combine two or more inputs into one output. As you will learn, optical coupling is more complex than its electronic counterpart because of the nature of optical signals. This chapter will explain how optical couplers work and describe the technologies used. It also will cover other important passive components not intended specifically for WDM applications, including attenuators and optical isolators.

Coupler Concepts and Applications

Couplers connect three or more points.

Connectors and splices join two fiber ends together. That's fine for sending signals between two devices, but many applications require connections to more than two devices. A coupler makes fixed connections among three or more points. (Switches also make connections among three or more points, but they're active devices that make temporary connections and are covered in Chapter 16.) Some couplers are called *taps* because they divert part of a signal going through a communication system to another point.

Optical couplers are often packaged inside a box, which protects the coupler from the environment. This box typically has connector adapters on the outside, as shown in

FIGURE 14.1
Optical coupler is packaged with connectors on the outside.

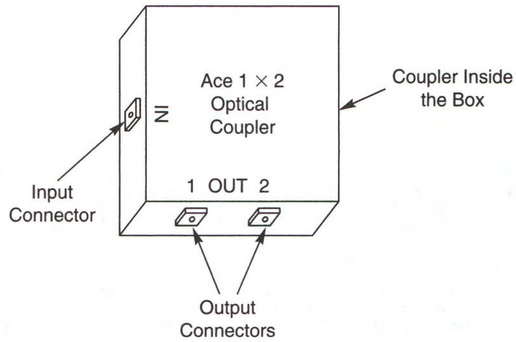


Figure 14.1, so the packaged optical coupler includes optical connectors. That may sound strange, but it's really no different from a telephone line splitter that has one plug for the input line and two for the output lines.

Couplers are used in many places that you may not notice. For example, you need a coupler to connect both a telephone and an answering machine to the same telephone line. The coupler may plug into the wall and give you two adjacent sockets, one for the phone and the other for the answering machine. It may be attached to the back of the answering machine, so you see two sockets, one for the line to the wall, the other for the line to the phone. Or it may be inside a single unit that contains both a phone and answering machine, dividing the signals between the two units in the same box. But the coupler must be there.

Couplers and taps are easy to make for electronic equipment. Electric current flows as long as you have physical contact between conductors; you don't have to line them up carefully, as you must with fiber cores. In addition, electronic signals usually are in the form of voltage. If you hook 1, 2, or 20 identical resistors across an *ideal* voltage source, each will see the same voltage signal as shown in Figure 14.2. Of course, putting more resistors in parallel across a *real* voltage source lowers the total resistance, so the voltage across the load will drop, depending on transmission-line resistance and other source characteristics. However, if the system is carefully designed, many loads in parallel will all have voltages close to what they would see individually. Thus electronic coupling can be as simple as hooking up wires to a signal source.

An optical signal must be divided among output ports, reducing its strength.

Optical signals are transmitted and coupled differently than electrical signals. First, you have to direct light into fiber cores, not merely make physical contact anywhere on the conductor. In addition, the nature of the optical signal is different. An optical signal is not a potential, like an electrical voltage, but a flow of signal carriers (photons), similar in some ways to an electrical current. Unlike a current, an optical signal does not flow *through* a receiver on its way to ground. The optical signal *stops* in the detector, which absorbs the light. That means you cannot put multiple fiber-optic receivers in series optically, because the first would absorb all the signal (except in very rare circumstances). If you want to divide an optical signal between two or more output ports, they must be in parallel. However, because the signal is not a potential, you cannot send the whole signal to all the ports. You must divide it between them, so no terminal receives a signal as strong as the input. Divide an optical signal equally between two terminals, and each gets half, as shown in Figure 14.2.

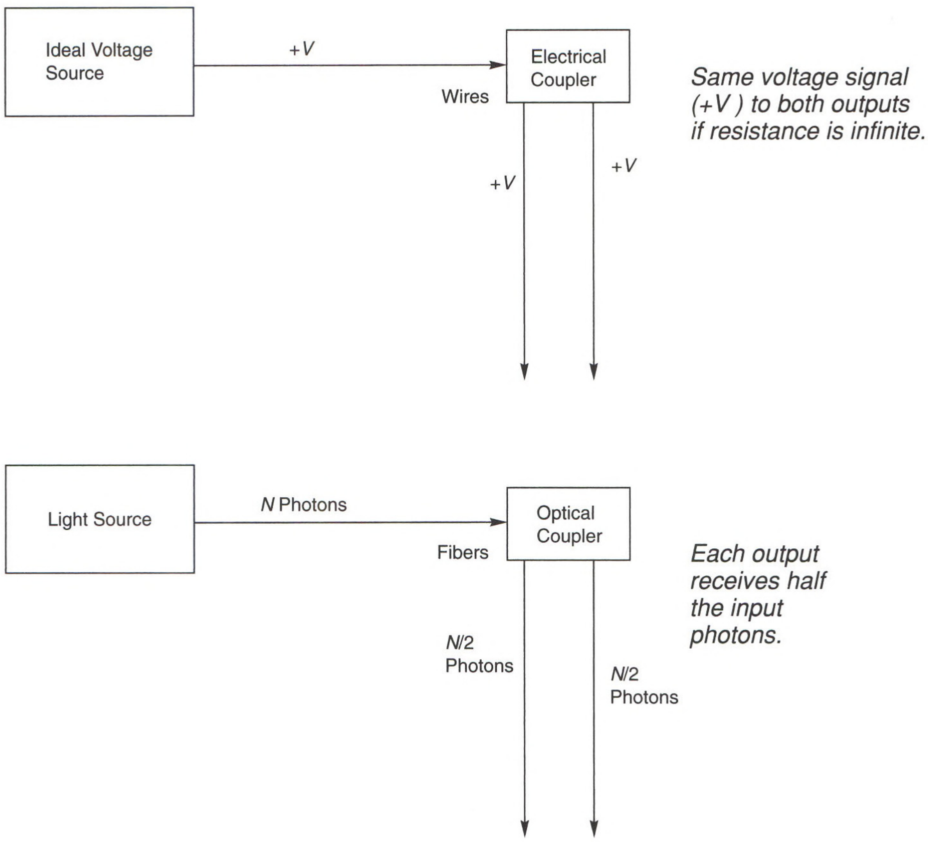


FIGURE 14.2
Optical and electronic couplers.

The need to divide an optical signal limits the number of terminals that can be connected to a passive coupler, which divides the input photons. With more ports, less signal reaches each one if the signal is divided equally, as shown in Table 14.1. Each doubling of the number of outputs reduces signal strength by 3 dB. Add too many outputs, and the signal grows too weak to detect reliably. The maximum number of ports depends on receiver sensitivity and other elements of system design.

The loss shown in Table 14.1 is the best case possible, assuming all the input light emerges from one of the outputs. In practice, things aren't that good, particularly if the coupler has many output ports. You can divide a signal in half efficiently, but dividing it into 50 or 100 equal parts is harder; some inevitably gets lost, reducing output signal strength. The difference between input signal and the sum of all the outputs (P_1 to P_n) is called *excess loss*.

$$\text{Excess loss (dB)} = -10\log\left(\frac{(P_1 + P_2 + \cdots + P_n)}{P_{\text{input}}}\right)$$

Note that Table 14.1 assumes the input signal is divided equally among the output ports. This does not have to be the case; you can design couplers that send 90% to one output

Table 14.1 Loss from splitting signals equally in passive couplers with no excess loss

Number of Output Ports	Fraction of Input in Each Output	Loss in dB
2	0.5	3.01
4	0.25	6.02
5	0.2	6.99
8	0.125	9.03
10	0.1	10
15	0.067	11.76
20	0.05	13.01
25	0.04	13.98
50	0.02	16.99
100	0.01	20
200	0.005	23.01
400	0.0025	26.02
1000	0.001	30

and 10% to a second. It also assumes that the couplers are passive devices, which draw no input power and merely divide the input power among output ports. Most couplers fall into that category, but there are a few exceptions, which I will explain later.

Coupler choice and design depend on applications.

Couplers have many different applications, so many types have been developed, which divide signals in different ways. Dividing signals between two outputs is the simplest example. As shown in Figure 14.3, couplers may need to split off a small fraction of the signal for each of several terminals, deliver identical signals to many different terminals, or direct different wavelengths to different places. Each of these applications requires a different type of coupler.

In the local-area network of Figure 14.3(a), you need to direct a small fraction of the optical signal from the server to each terminal. Thus you might use a coupler that transmits 90% of the signal through the network and diverts only 10% to each terminal. (This turns out to be rather inefficient, because coupler losses accumulate around the ring, so real local-area networks usually use different architectures.)

For cable-television distribution, shown in Figure 14.3(b), you want to divide the same signal into many equal portions, one for each subscriber. For this application, you use a simple 1-to-*n* splitter, which divides the signal equally among *n* outputs.

For wavelength-division demultiplexing, shown in Figure 14.3(c), you want to separate several wavelengths carried in the same fiber and distribute them to different places. Although you can consider this as a type of coupler, wavelength-division multiplexing has become so important it is covered separately in Chapter 15.

These examples highlight some functions couplers can serve in fiber-optic systems. They can combine signals from different sources, separate signals carried at different wavelengths

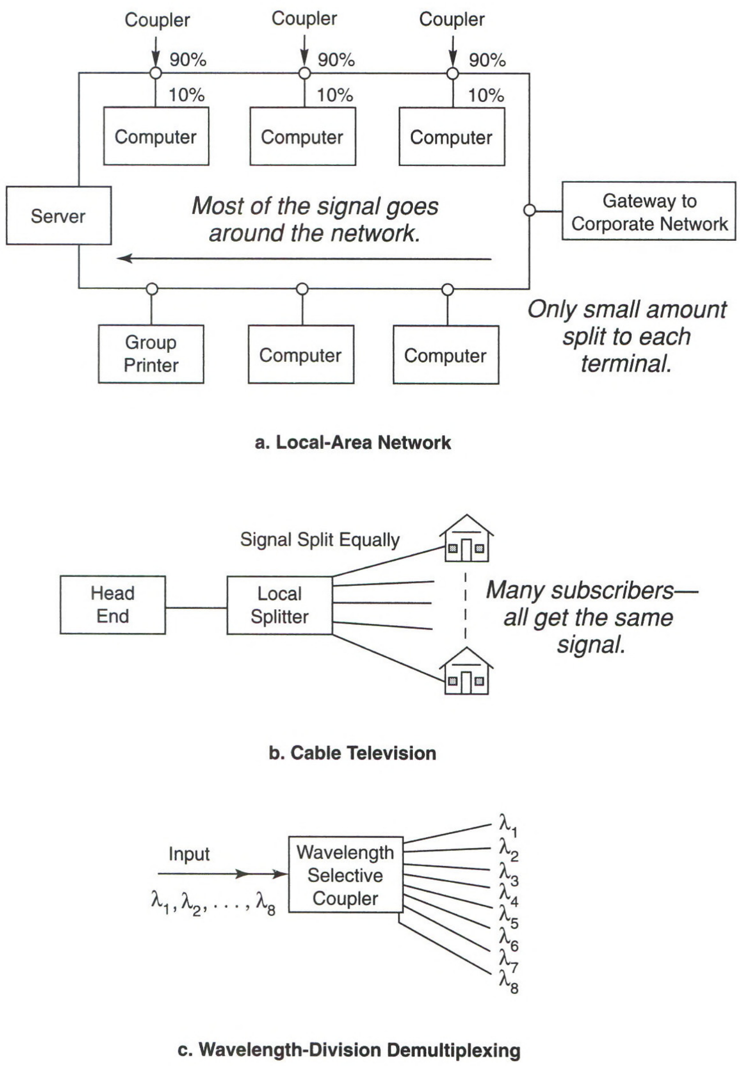


FIGURE 14.3
Different coupler applications: (a) tapping signals in a local-area network; (b) delivering cable television to many subscribers; and (c) splitting wavelengths.

and route them to different destinations, or split signals among two or more receivers. Note that the couplers do not change the signals; they merely combine, divide, or separate them.

Coupler Characteristics

Several optical characteristics determine the use and function of couplers. The most important of these are:

- Number of input and output ports
- Signal attenuation and splitting

- Directionality of light transmission (which way the light goes through the coupler)
- Wavelength selectivity
- Type of transmission: single- or multimode
- Polarization sensitivity and polarization-dependent loss

Number of Ports

The number of input and output ports depends on the application.

Outputs are usually, but not always, distinct from inputs.

Various applications require different numbers of input and output ports. For example, to split one input between two outputs, you need a 1-by-2 (1 input, 2 output) coupler. To divide one signal between 20 outputs, you need a 1-by-20 coupler. And if you want to combine 10 inputs and distribute the combined signal to 10 outputs, you need a 10-by-10 coupler.

In most cases, the inputs are distinct from the outputs, but in some cases they are not. For example, a 1-by-2 coupler implicitly is dividing the signal from one input port between a pair of different output ports. However, it is not automatically clear if a 10-by-10 coupler has 10 terminals that serve as both inputs and outputs, or 10 inputs and 10 distinct outputs (a total of 20 terminals). Usually the input and output ports are distinct, but not always, depending on the technology chosen, as you will learn later.

Signal Splitting and Attenuation

The number of ports alone does not tell how the signal is divided among them. Most couplers divide signals equally among all output ports, but some divide the light unequally. For example, a coupler that follows an optical amplifier may split off 1% of the output signal to an optical performance monitor, which verifies that all the expected optical channels are present in the output. Another example is unequal division of a signal between fibers delivering signals to receivers at different distances from the coupler.

Both signal splitting and excess loss contribute to port-to-port attenuation. As you saw in Table 14.1, a 3-dB loss is inevitable when splitting an optical input signal equally between two outputs. A coupler that delivers 90% of the input to one output and 10% to the other has loss of 0.46 dB on the 90% port and 10 dB on the 10% port. Excess loss, as mentioned earlier, is essentially the light wasted within the coupler, which does not reach one of the outputs. Generally excess loss is small, but it is not safe to ignore. Specified port-to-port losses include both splitting losses and excess loss.

Port-to-port attenuation also may be specified for *undesired* light, such as signals going the wrong way through a directional coupler, or wavelengths that are supposed to go out other output ports. These values essentially measure noise.

Directionality

Transmission depends on which way light goes in a directional coupler.

Many couplers are sensitive to the direction of light passing through them. They're not exactly one-way streets, but they tend to keep light going in the same direction. Figure 14.4(a) shows an example of one such *directional coupler*, where incoming light branches between two diverging outputs, like a waveguide that splits. Light that enters the

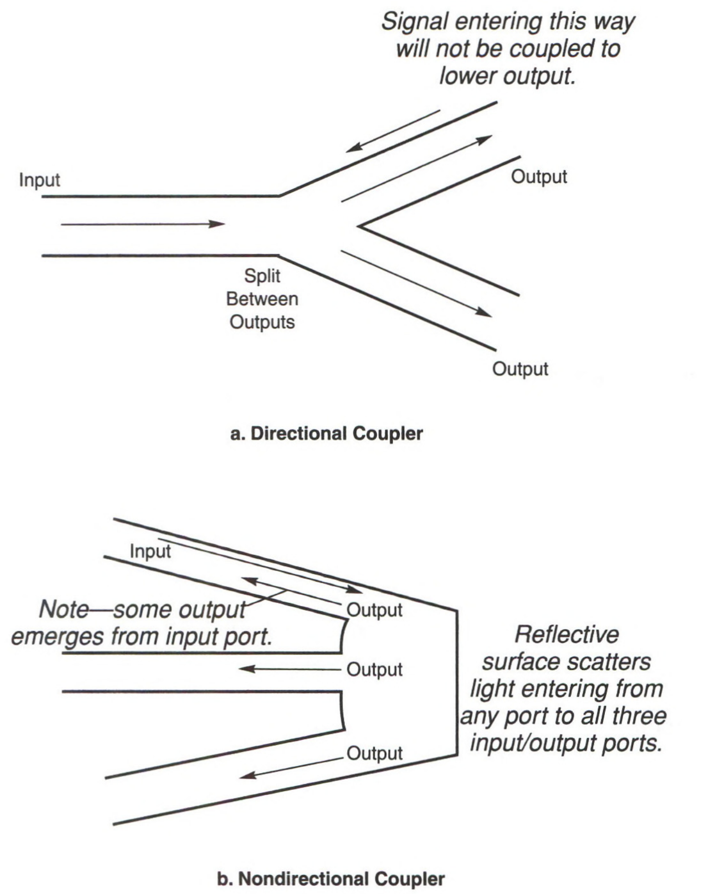


FIGURE 14.4
Directional and nondirectional couplers.

left port is split between the two outputs on the right side of the figure. However, if light enters the upper-right port, virtually all of it will go to the left port because of the coupler geometry. (A small fraction of light will reach the lower right port, but the loss will be high.) It's as if the waveguides were grooves and you were rolling marbles down them—once in a while the marble might bounce out the lower-right port, but most times it would go to the right.

Other couplers show little or no sensitivity to light direction. Figure 14.4(b) is one example, where light entering from the three ports on the left is reflected from a mirror on the right, which scatters light to all three ports. It doesn't matter which port the light enters; reflected light emerges from all three—including the input port. Such a coupler mixes the light from all inputs and delivers it to all outputs.

Most directional couplers are really *bidirectional* devices; that is, they can transmit light in either direction, but the light keeps going in that direction. The 1-by-2 coupler in Figure 14.4(a) is such a device. If you direct light through the upper-right port, it will keep going in the same direction and emerge through the single port at the left. Note the difference from a *nondirectional* coupler. In a bidirectional coupler, light going in a port on either side emerges only from the ports on the other. In a nondirectional coupler, light going in any one port emerges from all the ports, including the input. There isn't much demand for truly nondirectional couplers, but they can be made if you need them.

Generally, directionality or bidirectionality is an advantage in couplers, because it sends the signal in the direction you want it. Light headed in the wrong direction—back toward the transmitter in an input fiber, for example—can cause problems such as generating noise in laser transmitters.

Directionality or suppression of reflection back toward the source generally is measured in decibels. If a 1-mW (0-dBm) signal goes through a coupler with 50-dB directionality, only 0.01 μW (−50 dBm) will go in the wrong direction.

Wavelength Range and Selectivity

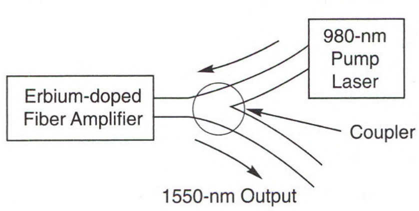
The mechanisms that divide or combine light in couplers typically depend in some way on the wavelength of light being transmitted. In some cases the dependence may be quite small, so the coupling ratio varies little between, say, 1200 and 1650 nm. In others the variation can be quite strong, directing wavelengths just a nanometer apart out different ports. These extremes represent two different classes of couplers.

Properties of wavelength-insensitive couplers vary little with wavelength.

Wavelength-insensitive couplers change their transmission little over their intended operating range. They are used in applications where light of all wavelengths is supposed to be treated equally. For example, a wavelength-insensitive coupler would be used in a system where the transmitter wavelength is not specified precisely, but the coupler has to split the signal the same way over the entire range of possible operating wavelengths. Such couplers also may be used to divide multiwavelength signals so all outputs contain all optical channels. One example would be splitting off a small fraction of optical amplifier output to an optical performance monitor to verify transmission on all channels between 1530 and 1565 nm. Performance of these couplers is specified as the same within a certain tolerance over a range of operating wavelengths.

Wavelength-selective couplers intentionally send light of different wavelengths in different directions. They are used in wavelength-division multiplexing, covered in Chapter 15. As you will learn, there are various types. Some separate widely spaced wavelengths, such as the 980-nm light from pump lasers and 1550-nm band optical signals in optical amplifiers, as shown in Figure 14.5. Others separate optical channels that are spaced closely in wavelength. The devices usually are called wavelength-division multiplexers (or demultiplexers), but strictly speaking they are special-purpose couplers.

FIGURE 14.5
Wavelength-selective coupler.



Coupler transmits 980-nm pump through top port and 1550-nm amplifier output through bottom port.

Other Transmission Sensitivities

As you will learn later in this chapter, several technologies can be used for couplers. Some of these coupler designs are limited to either single- or multimode fiber. These should be clearly identified.

Light transmission in some couplers is a function of the polarization of light, which can cause an effect called *polarization-dependent loss.* That is, the transmission of vertically polarized light differs from that of horizontally polarized light. This can be a problem because most fiber-optic systems do not constrain polarization. If the coupler loss depends on polarization, random variations in input polarization can essentially modulate the light output, inducing noise and degrading signal quality. The larger the polarization-dependent loss, the more significant this noise becomes.

Coupler Types and Technologies

Couplers may look superficially similar, but there are several distinct families and various underlying technologies. The names vary to some extent among manufacturers. The configurations or types reflect the function of the coupler. Various technologies are used.

Coupler Configurations

Coupler configurations define the function, often by the number of input and output ports. The four main types are shown in Figure 14.6 and described next:

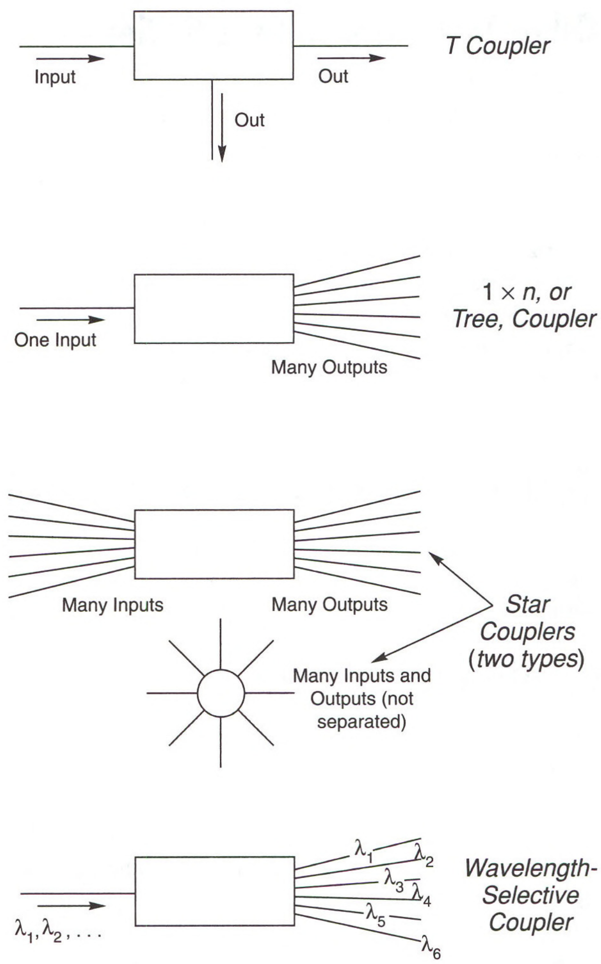
T couplers are three-port devices.

T and Y couplers, sometimes called *taps,* are three-port devices, which split one input between two outputs. They may divide the signal equally between the two outputs or split it in some other ratio. Some T couplers are analogous to electrical taps that take part of a signal from a passing cable and relay it to a terminal; they are often shown as one fiber coming off a cable in a T configuration, as in Figure 14.6. Others have a Y-shaped geometry, with two outputs branching at an angle from one input, and are called Y couplers. The directional coupler in Figure 14.4(a) is an example of a Y coupler. They are often—but not always—directional.

Tree, or 1-to-n, couplers generally take a single input signal and split it among multiple outputs, as shown in Figure 14.6. Some have a pair of inputs that are each divided among multiple outputs. Some may combine multiple inputs to one or two outputs, so they actually are combiners. They are generally directional.

Star couplers get their name from the geometry used to show their operation in diagrams such as in Figure 14.6, a central mixing element with fibers radiating outward like a star. They have multiple inputs and outputs, often (but not always) equal in number. There are two basic types. One type is directional, mixing signals from all input fibers and distributing them among all outputs, like the upper star coupler in Figure 14.6, often made by fusing fibers together. These are bidirectional devices because they also can transmit light in the opposite direction. A second is nondirectional, instead taking inputs from all fibers and distributing them among all fibers—both input and output—as with the lower star coupler shown in Figure 14.6.

FIGURE 14.6
Important coupler types.



Wavelength-selective couplers distribute signals according to their wavelength.

Wavelength-selective couplers distribute signals according to their wavelengths. Their main uses are to route WDM signals to their proper destinations and to separate wavelengths transmitted for different purposes through the same fiber, such as separating the light pumping an optical amplifier from the amplified signal. Wavelength-selective couplers are supposed to block other wavelengths from reaching the wrong destination. Chapter 15 covers them in detail.

Bulk and Micro Optics

In the world of fiber optics, *bulk optics* are conventional lenses, mirrors, and diffraction gratings, the sort of things you can hold in your hands. Bulk optics do not have to be large; they may be made quite small to match the dimensions of optical fibers and light sources. Such *micro optics* may be tiny, but they are still based on the same optical principles as larger bulk optics, so I will cover them together.

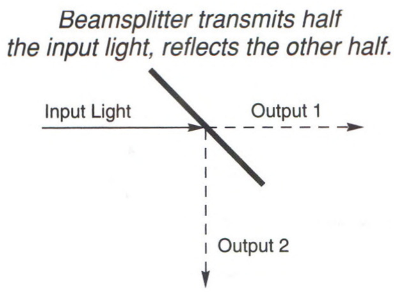


FIGURE 14.7
Bulk optical coupler: A beamsplitter divides a signal in half.

Bulk optics were the basis of many early types of couplers, and they still work. Figure 14.7 shows a simple example, the use of a device called a *beamsplitter* to split one input signal into two outputs. Like a one-way mirror, the beamsplitter transmits some light that hits it and reflects the rest. Collect the light from the two outputs in fibers, and you have a T coupler.

Micro optics are tiny versions of conventional lenses and other optical components, shrunk in size to work with fibers.

Bulk optical couplers often include lenses that expand, collimate, or focus light. The simple coupler of Figure 14.7 generally works better if a lens expands the light emerging from a fiber and focuses it onto a large area of the beamsplitter. This function is *collimation,* and such optics are called *collimators.* Then additional lenses focus the output beams into output fibers. Standard lenses with curved surfaces may be used; generally they are tiny, to match the sizes of fibers.

Alternatively, gradient-index (GRIN) lenses (or rods) may be used. These are rods or fibers in which the refractive index of the glass changes either with distance along the rod or with distance from the axis. The refractive-index gradient makes GRIN lenses focus light in a way functionally equivalent to ordinary lenses, but GRIN lenses are smaller and easier to adapt to fiber systems.

GRIN lenses are rods or fibers with refractive index graded so they act like ordinary lenses.

Another application of bulk optics is the use of a diffraction grating to separate wavelengths. A diffraction grating is an array of closely spaced parallel grooves, which act together to scatter light at an angle that depends on its wavelength, generating a rainbow of colors.

Fused-Fiber Couplers

Normally you can't transfer light between fibers just by touching them together. The light-guiding cores are covered by claddings that keep light from leaking out. If you want to couple light between fibers, you have to transfer it between the cores. That means you have to remove the claddings from one side of each fiber so the cores can touch. That is the basis of fused-fiber couplers, made by melting together fibers, usually with claddings removed partly or totally from one side, as shown in Figure 14.8. Often the fibers are twisted together to improve light transfer. Fused-fiber couplers sometimes are called *biconic* couplers, which should not be confused with biconic connectors, an early type in very limited use today. They are the most common technology used to make couplers.

Fused-fiber couplers are the most widely used type.

Although Figure 14.8 shows the cores merged, they don't have to merge completely in the middle zone as long as they come close. A phenomenon called *evanescent-wave coupling* can transfer light energy through a thin cladding or material with lower refractive index than the light-guiding zone. As you learned in Chapter 4, a small amount of the light energy guided

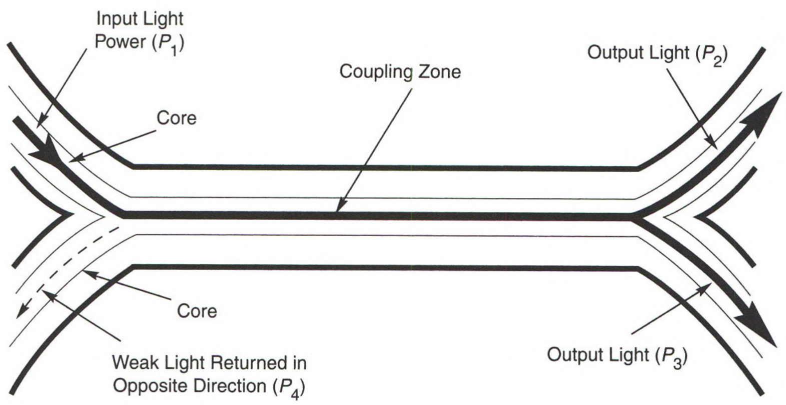


FIGURE 14.8
A 2 × 2 fused-fiber coupler.

in the core of an optical fiber actually penetrates a short distance into the cladding. This light is called the *evanescent wave,* and you can see its effect in single-mode fibers, where it makes the mode-field diameter larger than the core of a step-index single-mode fiber. Evanescent-wave coupling is important in both fused-fiber and waveguide couplers.

Fusing two fibers produces a 2 × 2 coupler with two inputs and two outputs. In practice, these are often turned into 1 × 2 couplers by cutting one fiber end inside the case. This design is functionally directional, although it is bidirectional in the sense that light can go through it in either direction. If light enters the fiber end at upper left in Figure 14.8, the only way light can reach the fiber end at lower left is by reflection or scattering. Directivity is measured by comparing the input power, P_1, to the power reflected back through the other fiber end on the input side, P_4:

$$\text{Directivity (dB)} = -10 \log\left(\frac{P_4}{P_1}\right)$$

For a typical fused-fiber coupler, the directivity is 40 to 45 dB.

The details of fused-fiber coupler operation depend on whether the fibers are multimode or single-mode. In multimode couplers, the higher-order modes leak into the cladding and into the core of the other fiber; the degree of coupling depends on the length of the coupling zone, and does *not* depend on wavelength. In single-mode fibers, light transfers between the two cores in a resonant interaction that varies with length. If all the light enters in one fiber, it gradually transfers completely to the other, then transfers back as it travels farther, shifting back and forth cyclically. The distance over which the cycling takes place depends on the coupler design and the wavelength, as Chapter 15 will describe in more detail.

The fused-fiber coupler design can be extended to multiple fibers using the same basic principles. The important change is adding more fibers, so signals from all input fibers mix in the coupling zone and emerge out of all the output fibers. This approach can be used to make star couplers with many distinct inputs and outputs. Such multifiber fused couplers are bidirectional.

Planar Waveguide Couplers

As you learned earlier, optical fibers are not the only type of optical waveguides. Like fibers, planar waveguides confine light in a region of high refractive index surrounded by material with a lower refractive index. The planar waveguide may be a thin strip embedded in the surface of a flat substrate, as you saw in Figure 6.12, or it could be a strip deposited on the top of a flat substrate. Air and the substrate combine to serve the function of the cladding in a fiber.

Waveguide patterns are written using the same techniques that write integrated electronic circuits onto semiconductor wafers. They can branch or merge, making them the equivalent of fused-fiber couplers. A simple example is a Y-shaped structure that divides one input waveguide to form two outputs, as shown in Figure 14.9. (An actual split would be much smaller than shown.) If the outputs split at equal angles, as shown, the light divides equally between them. This approach can be extended to more outputs by adding Y couplers to divide the output signals. Alternatively, the input waveguide could be divided to give more outputs, but the power would not be evenly divided.

Simple waveguide couplers are branched planar waveguides.

Two closely spaced waveguides on the same substrate can also transfer light by evanescent-wave coupling through a thin layer of lower-index material, as in fused-fiber

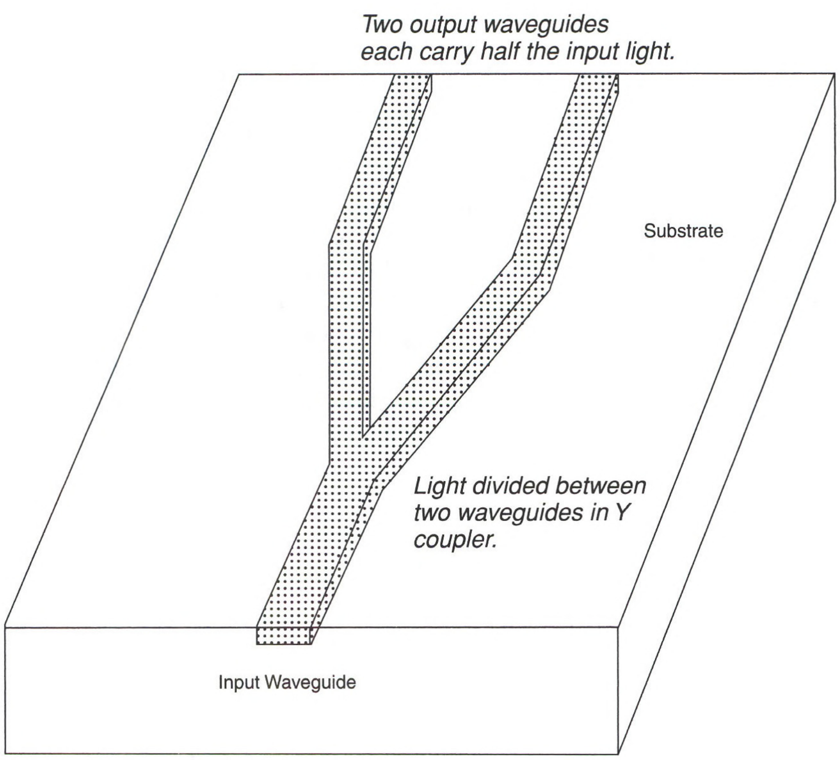


FIGURE 14.9
Planar waveguide splits in two, so light divides equally between arms of the Y coupler.

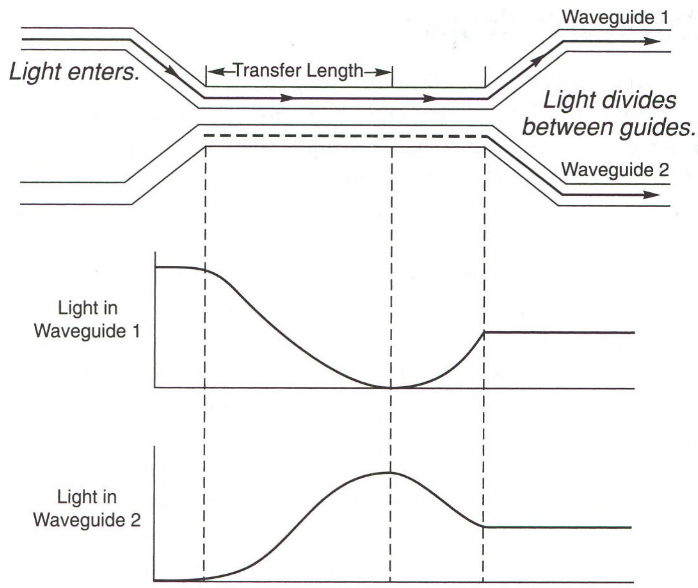


FIGURE 14.10 *Light transfer between two evanescently coupled waveguides.*

couplers. This type of waveguide device is called an *evanescent-wave coupler* and shown in Figure 14.10.

Evanescent-wave couplers depend on light leakage between two closely spaced waveguides.

An evanescent-wave coupler gradually transfers light between the two waveguides, along the region where the waveguides are closely spaced. In Figure 14.10, light enters in the top waveguide, and gradually transfers to the lower waveguides. This continues until all light shifts from the upper to the lower waveguide at a point called the *transfer length*, which depends on the optical characteristics of the waveguide. At this point, all the light is in the lower waveguide, and the process reverses, with the light starting to shift back from the lower waveguide to the upper one. Thus the distribution of light energy between the two waveguides oscillates back and forth between them with distance, as shown in the lower part of Figure 14.10. This oscillation stops at the end of the coupling region, determining the final distribution of light. The same process occurs in single-mode fused-fiber couplers.

Designers select lengths and optical properties of the two parallel waveguides to give the desired distribution of light (e.g., 50/50 or 75/25). In practice some light is lost within the waveguide and in transferring between the two waveguides.

Surface waveguides can be fabricated in complex patterns on a variety of materials. When they are made on the same substrate with many other devices, they are often called *integrated optics*, but then they usually contain active devices such as lasers, switches, or modulators. Chapter 16 covers such devices.

Active Couplers

An active coupler is a repeater with two or more outputs.

Devices called *active couplers* also look to the user as if they split signals from fiber-optic transmission lines, but if you look closely, they work quite differently. An active coupler is essentially a dedicated repeater in which the signal from a receiver drives two (or more) transmitters, which can generate optical and/or electronic output signals. This means that active couplers are not passive devices. However, they do function as couplers, so they are mentioned here.

Active couplers are mostly used in local-area networks. For example, a fiber that runs to a network node may drive a receiver that generates two electronic outputs. One goes to an optical transmitter, which generates an optical signal to send through the next length of fiber in the network. The other is transmitted in electronic form to the terminal attached to that network node. Other configurations also are possible.

Attenuators

Attenuators reduce light intensity uniformly across the spectrum.

As you learned in Chapter 11, too much light can overload a receiver. Attenuators reduce light intensity, by transmitting only a fraction of the input light. They are needed when a transmitter could deliver too much light, such as when it is too close to the receiver.

An *attenuator* is a type of optical filter, which should affect light of all wavelengths transmitted by the system equally. Attenuators are like sunglasses, which protect your eyes from being dazzled by bright lights. Fiber-optic attenuators generally absorb the extra light energy, which is too little to heat the attenuator noticeably. They should not reflect the unwanted light, because it could return through the input fiber to cause noise in a laser transmitter.

Most attenuators have fixed values that are specified in decibels. For example, a 5-dB attenuator should reduce intensity of the output by 5 dB. Attenuators designed for general optics use may have attenuation specified as the percent of light transmitted *(T)* or as *optical density.* Optical density is defined as:

$$\text{Optical Density} = \log_{10}\left(\frac{1}{T}\right)$$

This should look familiar, because it's close to the formula for attenuation in decibels, without the factor of 10. You can think of optical density as 0.1 times attenuation in dB, so a filter with optical density of 2 has a 20-dB loss.

Variable attenuators also are available, but they usually are used in precision measurement instruments.

If you're familiar with electronics, it may be tempting to think of an attenuator as an optical counterpart of a resistor. This is not a good general analogy. An attenuator does limit the flow of light like a resistor limits current flow—but resistors also serve other circuit functions, such as providing voltage drops, and controlling circuit loads. The only job of attenuators in a fiber-optic system is to get rid of excess light.

It's important to distinguish between attenuators and other types of optical filters. Attenuators should have the same effect on all wavelengths used in the fiber system. That is, if the attenuator reduces intensity at one wavelength by 3 dB, it should do the same at all wavelengths. Other types of filters typically do not affect all wavelengths in the same way. For example, a filter might transmit light in the 1530 to 1565 erbium-amplifier band, but have 50 dB attenuation in the 980-nm pump band. In fiber-optic systems, the term *filter* is used for filters in which light transmission varies significantly with wavelength; they are used in wavelength-division multiplexing, and covered in Chapter 15.

Optical Isolators

Optical isolators transmit light only in one direction.

Optical isolators are devices that transmit light only in one direction. They play an important role in fiber-optic systems by stopping back-reflection and scattered light from reaching sensitive components, particularly lasers. You can think of them as optical one-way streets with their own traffic cops or as the optical equivalent of an electronic rectifier (which conducts current only in one direction).

The operation of optical isolators usually depends on materials called *Faraday rotators*, which rotate the plane of polarization of light. The rotation is always by the same angle when seen from the viewpoint of the light source. But for light transmitted from sources on opposite sides of the Faraday rotator, the angles are in different directions. With a bit of smart design, this feature can separate light going in different directions, so light going in the desired direction gets through, but light going the wrong way is stopped.

Figure 14.11 shows a simple example. First consider light going from left to right, the desired direction. The input light is unpolarized, but it passes through a linear polarizer, which transmits only light polarized vertically. Then the Faraday rotator twists the plane of polarization 45° to the right. The light then encounters a second polarizer, which is oriented so it transmits only light with its plane of polarization oriented 45° to the right of

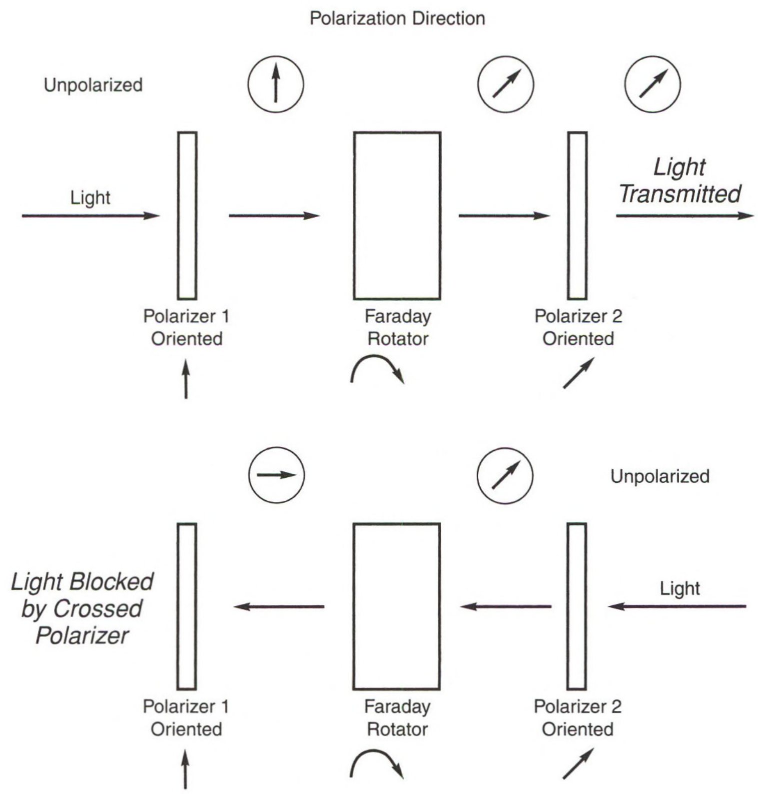


FIGURE 14.11
An optical isolator transmits light in only one direction.

vertical. That's all of the light going from left to right, so the signal goes through unimpeded except for a 3-dB loss because the input polarizer blocked half of the unpolarized input signal.

Now consider light going in the opposite direction, from right to left. The polarizer at right transmits only light polarized at 45° to the vertical, and the Faraday rotator turns the plane of polarization another 45° to the right. That makes the plane of polarization horizontal, so the light is blocked by the vertical polarizer at the left. A little stray light does leak through, but light headed in the wrong direction can be attenuated by 40 dB or more, protecting lasers from stray light that could induce noise.

One drawback of this simple design is that it's polarization sensitive. The input polarizing filter blocks half the input light that is not vertically polarized, causing 3-dB loss. More refined polarization-insensitive designs instead separate the input signal into two beams: one vertically polarized and the other horizontally polarized. One approach uses transparent crystals in which light travels at different speeds depending on its polarization. Prisms of such strongly birefringent materials separate vertically and horizontally polarized light so they follow different paths; these prisms are sometimes called *beam displacers.* They can be combined with focusing elements and Faraday rotators so that light traveling in one direction in focused from the input fiber into the output fiber, while light traveling in the opposite direction is defocused to prevent it from going into the input fiber. Although this design is a bit more complicated, it avoids 3 dB of loss.

Polarization-insensitive optical isolators do not have 3-dB internal loss.

Optical Circulators

The optical circulator is a cousin of the optical isolator in both its function and design. Its function is to serve as a one-way street for light passing through a series of ports, so light that enters in port 1 must go to port 2, and any light entering at port 2 goes to port 3, and so on. Like the optical isolator, it uses polarization to do its job.

An optical circulator sends light in one direction through a series of ports.

One way to make an optical circulator is with a pair of optical isolators. One can be inserted between port 1 and port 2, blocking light going backwards from port 2. A second can be inserted between ports 2 and 3, blocking light trying to go back from port 3 to port 2. However, these designs lose the blocked light.

Figure 14.12 shows a more elegant and efficient optical circulator, which is assembled from three types of components. Faraday rotators and birefringent beam displacers also are used in the optical isolators described above. Recall that the displacers separate light of different polarization, while the Faraday rotators always rotate the polarization by 45° from the viewpoint of a photon passing through them. If light goes back and forth through the same Faraday rotator, its polarization changes a total of 90°.

Optical circulators also include devices called *waveplates*, which also rotate the polarization by 45°, but in a different way. If light passes through a waveplate one way, it's rotated 45° to the right; if it goes through the other way, the light rotates 45° to the left. That means the net change on a round trip is 0°, so light that makes a round trip through a waveplate emerges with the same polarization it started with.

Now go back to Figure 14.12 and trace the paths of the two polarizations from port 1 to port 2. The vertically polarized input is deflected up, then rotated +45° by the waveplate

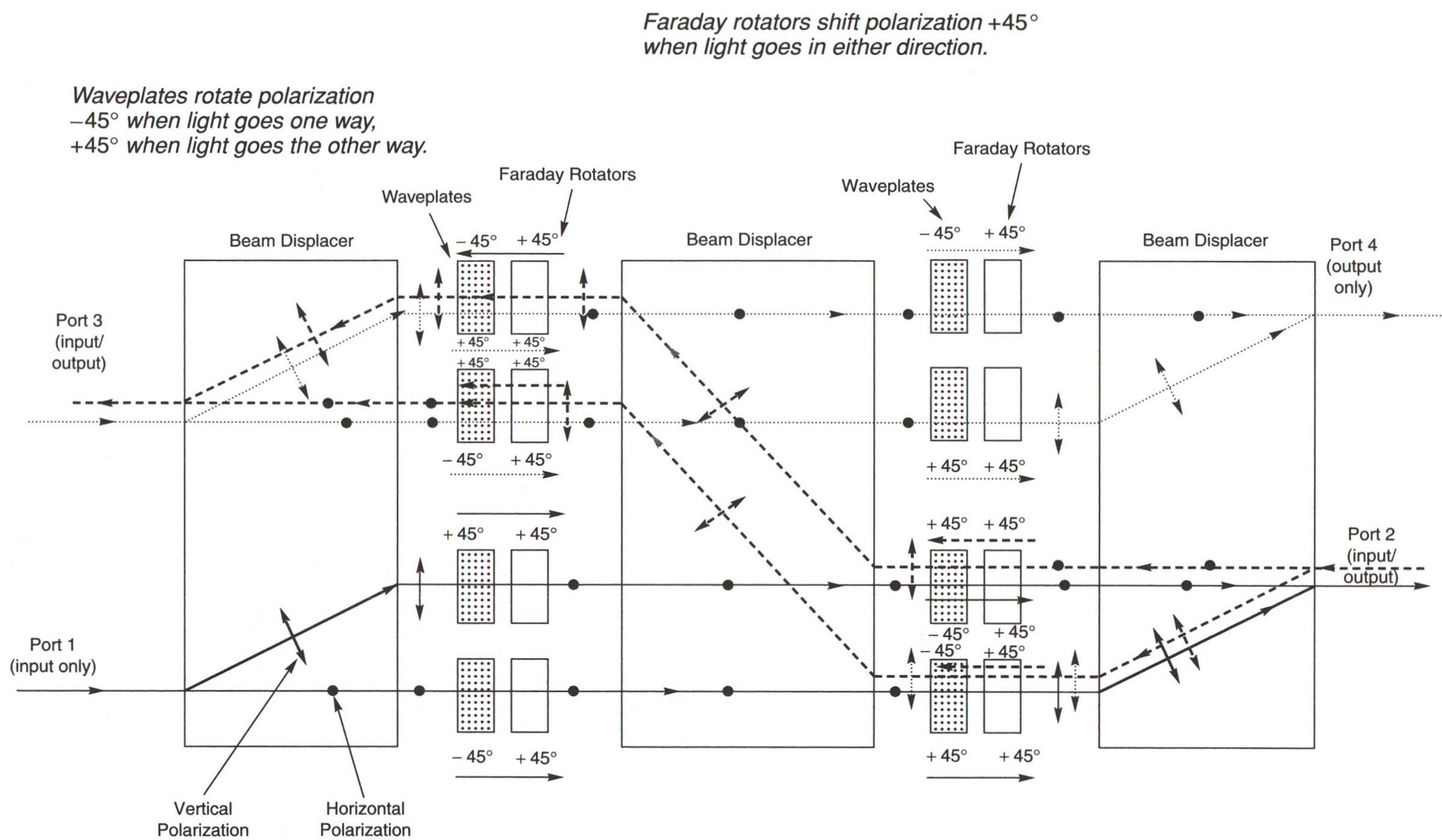


FIGURE 14.12

Optical circulator directs light from part 1–2, 2–3, and 3–4, without allowing it to go backwards.

and another +45° by the Faraday rotator, a total of 90°, making it horizontally polarized so it passes straight through the second beam displacer. Then it is rotated −45° by the waveplate and +45° by the Faraday rotator, a net change of zero, so it remains horizontally polarized through the third displacer and out port 2. The horizontally polarized input, in contrast, goes straight through the first displacer, and is rotated −45° by the waveplate and +45° by the Faraday rotator, a net of zero. It then goes straight through the second displacer. At the second rotator, it is rotated +45° by the waveplate and +45° by the Faraday rotator, a total of 90°, which makes it vertically polarized so the displacer bends it upwards—and aims it out port 2, where it is supposed to go.

The tricky part is following the path from port 2 to port 3 (right to left in Figure 14.12). The beam displacer splits the two polarizations so they pass through the second rotator. This time the top (horizontally polarized) beam is rotated +45° by the waveplate and +45° by the Faraday rotator, changing its polarization to vertical. The middle beam displacer bends the beam upward, and it emerges from the upper side of the middle beam displacer on its way to port 3. In this case, it is rotated −45° by the waveplate and +45° by the Faraday rotator, so it remains vertically polarized, and is deflected downward to port 3. The bottom (vertically polarized) light from port 2 is deflected downward, where the waveplate rotates it −45° and the Faraday rotator rotates it +45°, leaving it vertically polarized as it enters the middle beam displacer. It's bent upward, and arrives at the lower position on its way to port 3. Here the polarizer rotates it +45° and the Faraday rotator rotates it +45°, changing it to horizontally polarized light that goes straight through the beam displacer to port 3.

Each level of the optical circulator is identical, so the steps can be repeated as long as you want. The crucial tricks are separating the polarizations, routing them through different components, and taking advantage of the different ways Faraday rotators and waveplates rotate polarization.

What Have You Learned?

1. Couplers connect three or more fibers or ports. Dividing an optical signal among two or more ports reduces its strength because it divides the photons in the signal.
2. Several different types of couplers are used; their design depends on the application.
3. Direction is important in couplers. Most couplers are directional in the sense they transmit signals from one or more inputs to one or more outputs, with little light going from one input to another. Most designs also are bidirectional, in the sense that the input and output ports could be reversed to change light coupling.
4. T or Y couplers, or taps, are three-port devices. Tree, or 1-to-*n*, couplers divide one input among *n* output ports. Star couplers have multiple inputs and outputs. Outputs are usually distinct from inputs.
5. Wavelength sensitivity is important in couplers. It is desirable for wavelength-division multiplexing, but not for most other applications.

6. Many couplers are made from bulk or micro optics, such as beamsplitters.
7. GRIN lenses are rods or fibers with refractive index graded so they refract light like ordinary lenses.
8. Fused-fiber couplers transfer light between the cores of two fibers melted together. Single-mode fused-fiber couplers work differently than multimode versions. Multifiber fused-fiber couplers are possible.
9. There are two types of planar waveguide couplers. Some simply divide light between two waveguides branching in a Y from a single-input guide. Others rely on evanescent-wave coupling to transfer light between two parallel waveguides. Evanescent-wave couplers are sensitive to wavelength.
10. Active couplers are repeaters with two or more outputs.
11. Attenuators block light uniformly across a range of wavelengths to reduce signal strength at the receiver.
12. Optical isolators transmit light in only one direction. They rely on polarizing optics and Faraday rotators.
13. Optical circulators route light through a series of ports, feeding output from one port to the next, and taking input from the second port and routing it to a third. They rely on birefringent crystals, Faraday rotators, and other polarization rotators.

What's Next?

Chapter 15 covers wavelength-selective optics used for wavelength-division multiplexing.

Further Reading

Morris Hoover, "New coupler applications in today's telephony networks," *Lightwave,* Vol. 17, March 2000.

Luc B. Jeunhomme, *Single-Mode Fiber Optics: Principles and Applications* (Marcel Dekker, 1990). See Chapter 6, "Passive Components."

Questions to Think About

1. Suppose your input signal is −10 dBm and your receivers require a signal of at least 0 dBμ. You want to distribute signals to as many terminals as possible. If there is 3 dB of fiber loss between you and each receiver, how many terminals can you deliver signals to? How much coupler loss does this correspond to on each channel? Assume you can buy a star coupler with as many ports as you want, which has no excess loss.

2. Suppose that all star couplers available for the system described in Question 1 have excess loss of 3 dB. How many terminals can you reach with these couplers, and what is the total loss per channel?
3. An alternative design is to cascade a series of 3-dB T couplers. The first splits the signal in half, then each output has its own 3-dB coupler, dividing that output in half, yielding one-quarter of the original output. Adding more layers further divides the signal. Suppose you can get as many 3-dB couplers as you want and each one has no excess loss. How many terminals can you divide signals among in Question 1?
4. A local-area network includes 90/10 couplers, which split 10% of the input signal and deliver it to a local terminal. Suppose you have 10 of them in series and the input power is −10 dBm. What is the power delivered by the last coupler out each of its ports?
5. If your receiver requires 1 μW of power, how many more 90/10 couplers could you have in series before the 10% side does not deliver enough power for reliable operation? Assume the same −10 dBm input as in Question 4.
6. An optical amplifier delivers 0.5 mW/channel on each of 32 channels. You want to monitor its performance by diverting a small portion of its output to an optical performance monitor that requires 1 dBμ input per optical channel. What fraction of the output power do you need to divert to the performance monitor?
7. Neglecting excess internal losses, what is the difference in attenuation between the following two optical circulators? The first uses the simple optical isolators of Figure 14.11—one oriented from port 1 to 2 and the second from port 2 to 3, with a 50/50 T coupler splitting input signals from port 2 between two routes. The other is the more complex optical circulator of Figure 14.12.

Chapter Quiz

1. You have a coupler that divides an input signal equally among 16 outputs. It has no excess loss. If the input signal is −10 dBm, what is the output at any one port?
   a. −12 dBm
   b. −20 dBm
   c. −22 dBm
   d. −26 dBm
   e. −30 dBm
2. A 1 × 20 coupler has output signals of −30 dBm at every port if the input signal is −10 dBm. What is its excess loss?
   a. 0 dB
   b. 1 dB

c. 2 dB
d. 4.2 dB
e. 7 dB

3. A coupler splits an input signal between two ports with a 90/10 ratio. If the input signal is −20 dBm and the coupler has no excess loss, what is the output at the port receiving the smaller signal?

a. −21 dBm
b. −29 dBm
c. −30 dBm
d. −31 dBm
e. −110 dBm

4. What type of coupler could distribute identical signals to 20 different terminals?

a. T coupler
b. tree coupler
c. star coupler
d. M × N coupler
e. wavelength-selective coupler

5. What type of coupler divides one input signal between two output channels?

a. T coupler
b. tree coupler
c. star coupler
d. M × N coupler
e. wavelength-selective coupler

6. You find a coupler with four ports and no label on it. You measure attenuation from port 1 to the other three ports. The values are: −40 dB to port 2, 3 dB to port 3, 3 dB to port 4. What type of coupler do you have?

a. star coupler with three unequal outputs
b. tree coupler with three unequal outputs
c. a directional 2-by-2 coupler with two inputs and two outputs
d. a nondirectional T coupler
e. a broken coupler

7. A Y coupler that equally divides light between two outputs has a 3-dB loss on each channel. What is the right explanation?

a. The 3-dB figure is excess loss.
b. Half the photons that enter the coupler go out each output, corresponding to a 3-dB loss on each channel.
c. The coupler polarizes the light going out each port, causing 3-dB loss.

d. Every coupler has at least 3-dB loss no matter how it divides the input light.

e. The optics are dirty, causing loss of half the input light.

8. Evanescent waves cause light energy to transfer between channels in what type of coupler?

a. planar-waveguide coupler

b. single-mode fused-fiber coupler

c. bulk optical coupler

d. multimode fused-fiber coupler

e. a and b

f. b and d

9. An attenuator

a. is a filter that blocks one wavelength but transmits others.

b. polarizes input light, causing loss of the other polarization.

c. reduces light intensity evenly across a range of wavelengths.

d. selectively blocks photons produced by spontaneous emission.

10. How many polarizers does a simple polarization-sensitive optical isolator use to block transmission of light in the wrong direction?

a. none

b. 1

c. 2

d. 3

e. 4