CHAPTER

16

Optical Switches, Modulators, and Other Active Components

About This Chapter

Fiber-optic systems are no longer passive pipes that merely carry optical signals from point to point. Signals may be modulated in intensity, switched between fibers, shifted in wavelength, and modified in other ways. The potential of "optical networking" was over-promoted during the telecommunications bubble, but the need to operate on signals is growing with the volume of traffic and the size of the global telecommunications network. The devices that perform these operations on signals are called *active components.*

You have already learned about several types of active components. Light sources, transmitters, receivers, optical amplifiers, and wavelength converters are all active components. In this chapter you'll learn about optical modulators, optical switches, and other components that dynamically affect optical signals.

Defining Active Components

The distinction between active and passive components can be useful, but it also can be confusing, so it deserves a bit of explanation. Originally, active components were those that required power from an outside source while passive components drew no outside power. By this definition, a laser or optical amplifier is obviously an active component, and an optical fiber or attenuator is obviously passive. Yet the source of power doesn't necessarily say much about function.

Modulators and switches are active components.

Another approach is to consider how components affect a signal. In this sense, a passive component always performs the same operation on a signal, such as dividing it in half or attenuating it by a fixed amount. In contrast, an active device can change its effect on the signal, such as by modulating its intensity or switching it between fibers. This approach has the advantage of focusing on what a device does to the signal, but has its own limitations. If strictly applied, it might class a laser that generates a steady beam as passive because it does not affect the signal strength.

In practice, it's best to consider components as active if they either draw power from outside or modify the signal in changing ways. The most important active components in current optical systems—modulators and switches—do both. Some haziness in the definition is acceptable. The distinctions change as the technology evolves, and the main purpose here is not critical—it's a way of organizing this book into chapters of manageable size.

Modulators and Modulation

Light must be modulated to transmit a signal. As you learned in Chapters 9 and 10, the simplest modulation technique is to directly change the drive current passing through a laser or LED. Unfortunately, direct modulation runs into a number of limitations as speeds increase. The modulation rate, average output power, and difference between "off" and "on" states are all limited. Direct modulation also can distort analog signals and shift the output wavelength of any signal, an effect called *chirp*, which adds to chromatic dispersion.

External modulation improves system performance.

The importance of these limitations depends on the system design. If the signals are transmitted through one optical channel in a DWDM system spanning long distances, problems may appear with direct modulation at data rates around 1 Gbit/s. If the signals are sent a kilometer or two in a campus network using CWDM or only a single wavelength per fiber, direct modulation can work at 10 Gbit/s. In either case, when direct modulation does not meet performance requirements, you can turn to external modulation, in which a separate device called a *modulator* changes the intensity of the light from a constant laser or LED source. External modulation can be faster than direct modulation of a laser or LED, and does not affect the source wavelength.

An optical modulator changes how much light it transmits in response to an external control signal. Many types have been developed for other applications, but fiber-optic systems are particularly demanding because they require modulation at gigabit rates, much faster than most modulation mechanisms. For example, liquid crystal devices cannot respond fast enough for fiber-optic modulators, but are fine for laptop computer displays, which operate much slower.

Modern fiber-optic systems use two main families of modulators. *Electro-optic modulators* rely on changes in the way certain planar waveguides carry light. *Electro-absorption modulators* are semiconductor diodes that in their internal structure resemble lasers, but are switched between states that transmit and absorb light. We will look at them separately.

Electro-Optic Modulators

Electro-optic modulation depends on the *electro-optic effect*, a change in the refractive index of certain materials when an electric field is applied to them. The change affects light passing through the material virtually instantaneously. The velocity of light in a material is the speed of light in a vacuum divided by the refractive index, so increasing the refractive index slows down the light; reducing it speeds up the light. The change is proportional to the voltage applied to the material.

Electro-optic modulators rely on changes in refractive index caused by an electric field.

When you look at a waveguide, you measure the effect of this change in refractive index as a shift in the phase of the light waves compared to what the phase would have been without the applied voltage. A shift of half a wavelength—180°—would leave the shifted light completely out of phase with the unshifted wave. The phase shift normally is measured by this comparison:

$$\text{Phase shift } (\Delta\Phi) = 180° \times \frac{V}{V_{180}}$$

where V is the voltage applied to the modulator and V_{180} is the voltage needed to shift the phase a half-wavelength, or 180°.

Merely delaying the light modulates its phase but not its intensity. To modulate the intensity, an electro-optic modulator splits the input light equally between a pair of parallel waveguides. In the example shown in Figure 16.1, a modulated voltage is applied to one waveguide, but not to the other. This modulates intensity of the light where the two waveguides merge at the right. If the waveguides are equal lengths and the voltage is zero, the light waves are in phase when they combine, so the waves add constructively, producing a signal. The light is "on." However, if you apply the voltage needed to delay the signal by 180°, the

Delaying the light phase causes interference effects that modulate the output intensity.

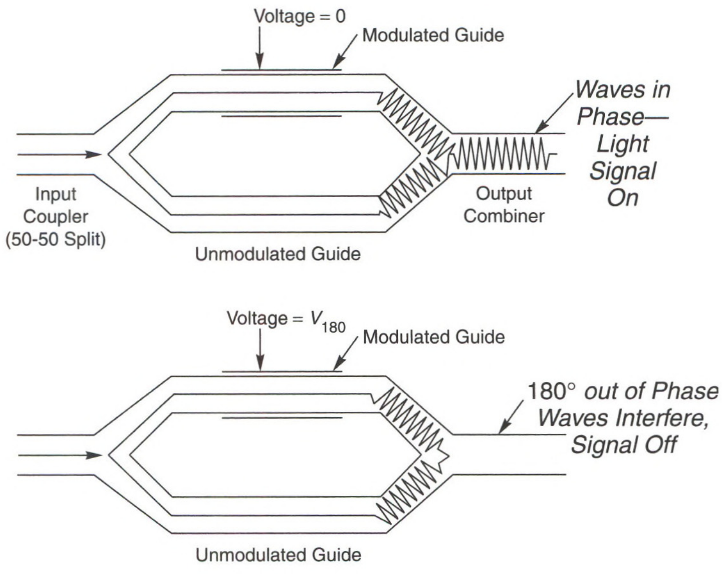


FIGURE 16.1
Simple electro-optic waveguide modulator.

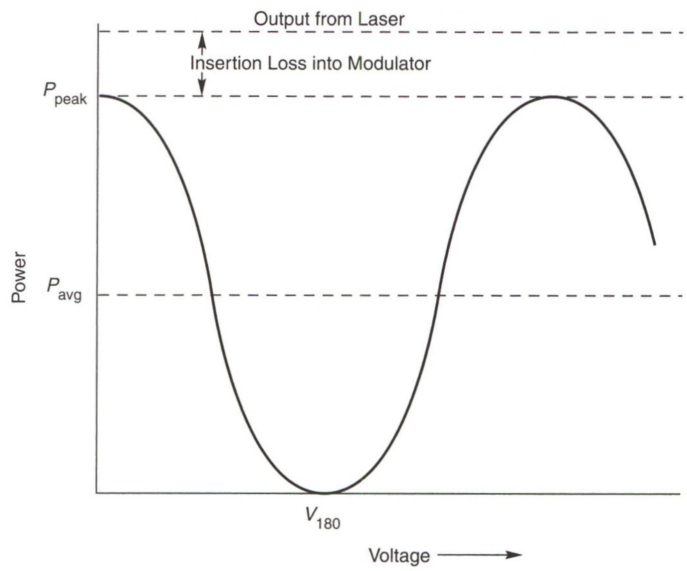


FIGURE 16.2
Variation in modulator output with voltage.

light in the two waveguides is out of phase when they merge. The two waves interfere destructively, canceling each other out, and the output intensity is nominally zero.

In practice, a little light remains when the signal is nominally zero, a quantity measured by the extinction ratio, which compares the output power P_{on} in the on state with that in the off state P_{off}.

$$\text{Extinction ratio (dB)} = -10 \log\left(\frac{P_{off}}{P_{on}}\right)$$

The same approach works for analog modulation, but in this case you adjust the voltage so the delay varies continuously between 0° and 180°. The result is a continuous variation in output intensity shown in Figure 16.2. (Note that the peak power is lower than the laser output by an amount that equals the insertion loss of the modulator, even when there is no voltage applied.)

Actual electro-optic modulators are more complex. Often voltages are applied across *both* waveguides, but with the opposite polarities, so the voltage delays the phase of one wave while speeding the phase of the other. In this case, a voltage of $+V_{180}/2$ is applied to one waveguide, and $-V_{180}/2$ is applied to the other, giving the same modulation with lower voltage. Typically the voltage signal applied to each channel is the sum of two signals, one a bias that sets the operating level, the other the modulating signal. For example, the bias may set the modulator to normally transmit a certain average power, with the variations in the modulation voltage changing the transmitted power above and below that level.

A further complication is that refractive index can vary with the polarization of light. In glass and many other materials, the refractive index is nearly identical for light of different polarizations, but in other materials it varies significantly with the orientation of the polarization relative to the crystal axes. Materials in which the refractive index differs significantly for vertically and horizontally polarized light are called *birefringent.*

Modulators are affected because the magnitude of the electro-optic effect also depends on polarization, so an applied voltage does not change the refractive index the same amount for vertically and horizontally polarized light. Thus an electric field that delays vertically polarized light by 180° may delay horizontally polarized light only 120°, so interference would not cancel out the horizontally polarized component of the light. One way to avoid this problem is by using a polarizing filter to block the undesired polarization before the light reaches an electro-optic modulator, so only one polarization is transmitted.

In theory, electro-optic modulators can be made of any material that displays the electro-optic effect and is transparent at the signal wavelength. In practice, the usual material for use at 1.3 and 1.55 μm is lithium niobate ($LiNbO_3$). Waveguides are made by diffusing titanium or hydrogen into the lithium niobate, raising the refractive index of a narrow stripe that forms a waveguide. One process raises the refractive index for one polarization but depresses it for the other, so only one polarization stays in the guide, while the other diffuses into the substrate. The goal is to eliminate the need to polarize light before sending it through the modulator.

Electro-optic modulators are made of lithium niobate.

Lithium niobate modulators are widely used today. The technology is well-developed and they can be modulated at rates to 40 Gbit/s for digital transmission. As waveguide devices, they can be integrated with some other optical devices. However, they cannot be integrated with light sources because lithium niobate is not a light emitter.

Electro-Absorption Semiconductor Modulators

An electro-absorption semiconductor modulator is a waveguide device based on different principles than the electro-optic modulator. The electro-absorption modulator has a structure similar to that of an edge-emitting semiconductor laser, and the two can be integrated on the same chip, as shown in Figure 16.3. In this arrangement, the laser and modulator share an active layer, so light generated within the laser stripe is coupled directly to the modulator waveguide.

An electro-absorption modulator is a semiconductor diode that is reverse-biased so modulation makes it absorb rather than emit light.

Despite their common structure, an electro-absorption modulator operates differently than a semiconductor laser. The laser is forward-biased so current flows through it, causing current carriers to recombine and generate light. The modulator is operated with a reverse bias, like a *pin* photodetector. When the modulator is unbiased, no current flows and it is transparent to the laser wavelength. However, when the bias voltage is applied, the laser light can produce electron-hole pairs that are pulled in opposite directions by the bias voltage,

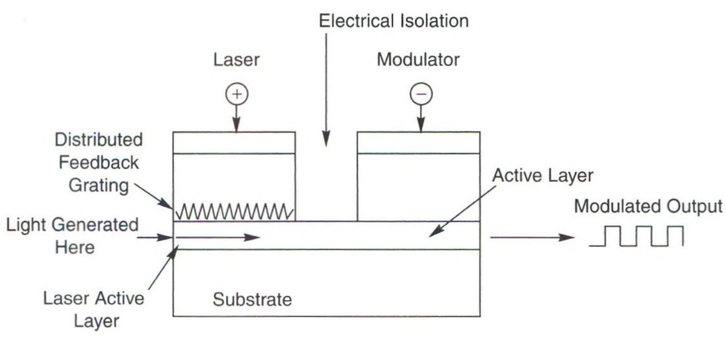


FIGURE 16.3
An electro-absorption modulator integrated with a semiconductor laser.

causing a net absorption at the laser wavelength. Increasing the bias increases the absorption, blocking the beam.

The laser and modulator are electrically isolated from each other. A steady current drives the laser, so it generates a steady optical output. The input signal drives the modulator. For zero applied voltage, the optical output is at its highest level. Applying a higher voltage to the modulator increases light absorption. (Note that this means that high voltages generate no light output.)

Although the laser and modulator sections of the integrated structure have similar structures, they are not identical. The structure of the active layer also differs between the two. The laser may include a distributed-feedback grating in the cavity or a distributed Bragg grating in the waveguide. Thicknesses of the active layers differ, as does the doping that differentiates between the laser and modulator sections. Nonetheless, the two devices can be fabricated on the same substrate, forming a single, integrated light source and modulator.

Like electro-optic modulators, electro-absorption modulators are polarization sensitive, although integrating them on the laser chip simplifies packaging. They are made from InGaAsP semiconductors, so they can readily match laser wavelengths.

Variable Filters and Dynamic Gain Equalization

Variable filters change too slowly to modulate a light signal.

Other types of modulators are available, but they change the intensity of transmitted light too slowly to be used as external modulators. Some that operate slowly are considered variable attenuators, which were covered in Chapter 15. (I warned you the definitions could be hazy.) Others can be used as switches, covered later in the chapter. Some are used as dynamic filters, which can be adjusted using feedback loops to control system performance. Dynamic filters are used in dynamic gain equalization systems, which monitor power on all optical channels in a WDM system so they can equalize power levels at all wavelengths. Power equalization uses feedback from the optical channel monitor to control dynamic filters that selectively attenuate certain channels. Let's look at a few examples.

In Chapter 15, we mentioned acousto-optic variable filters, in which acoustic waves create refractive-index variations in a crystal that deflect a fraction of the light passing through the crystal, reducing the transmitted intensity. The amount of reduction depends on the wavelength of the light and the frequency of the sound wave. Inducing multiple acoustic frequencies into the crystal can change attenuation over a range of wavelengths for use in dynamic gain equalization in a WDM system.

An alternative is thermo-optic modulation in planar waveguides. Heat changes the refractive index of the waveguide, so attaching heaters to one of a pair of waveguides can modulate the phase of light going through that guide. Combining light from the heated guide with light from the unheated guide modulates intensity the same way that electro-optic phase modulation does in an electro-optic modulator.

Liquid crystal devices also can be used as variable attenuators by varying their transmission, as in displays. LCDs respond much too slowly to modulate a laser beam with a signal, but they are adequate for variable attenuators, which don't require such high-speed response.

Diffractive MEMS change their reflectivity by shifting phase.

Another interesting approach is based on *micro-electro-mechanical systems* (MEMS). MEMS are arrays of micro-mechanical devices etched from silicon and integrated with electronic control circuits. For optical applications, MEMS are made with thin reflective

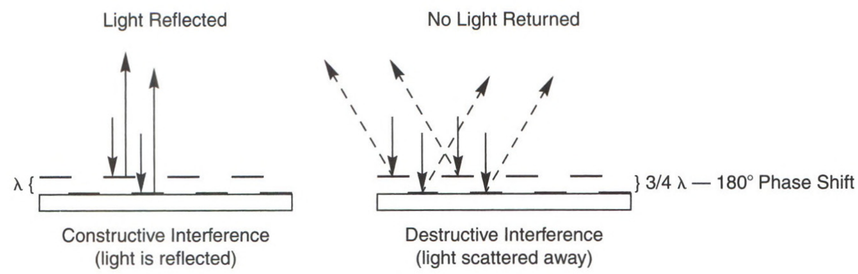


FIGURE 16.4
Diffractive MEMS device changes its reflectivity by shifting the phase of reflected light.

structures that move in response to electrical signals passing through circuits beneath them. Figure 16.4 shows a two-layer MEMS structure that can be used as a variable attenuator. One layer is an array of parallel reflective stripes suspended above the second layer, a refractive substrate. Moving the suspended upper layer a quarter wavelength relative to the substrate shifts the phase of the reflected light 180° relative to that of light from the substrate, shifting between constructive and destructive interference. Smaller variations in spacing adjust the intensity of the reflected light.

Switching in Optical Networks

Earlier you learned that the telecommunication network can be seen as an array of pipes and switches. The switches are the key difference between the old fiber-optic systems that merely piped signals from point to point, and the emerging optical network. *Optical switches* allow an optical network to process and direct light signals, as well as pipe them from place to place. This greatly enhances the functionality of an optical network, and makes optical switches very important.

Optical switches allow an optical network to process signals optically.

Switches serve various functions in telecommunications, and you should understand a bit about these applications before looking at specific switches. The most familiar type of switching is directing signals from point to point. The telephone network and the Internet do this in different ways, but the end user does not see a big difference without looking closely. Users merely know that they dial a phone number or enter an Internet address.

Other switching functions are less obvious to users. Telecommunications companies install switches to route signals around failed equipment, so a single failure won't knock out an entire telecommunication system. This function is called *protection switching*, and it relies on having backup routes. One common approach is to connect several cities in a ring that has extra capacity reserved. A cable break triggers the protection switch to divert signals that would have gone through the broken fibers to pass through the reserve fibers, as shown in Figure 16.5.

Telecommunication companies are making increasing use of switches to change the services they provide to customers, a process called *provisioning*. Traditionally, carriers sent technicians to physically connect lines to customers, but now that the network is changing faster, it is more economical to install switches and make the changes remotely. A similar function is dynamically changing the transmission capacity of parts of the network to meet special needs. For example, a carrier might reconfigure the network around a sports stadium

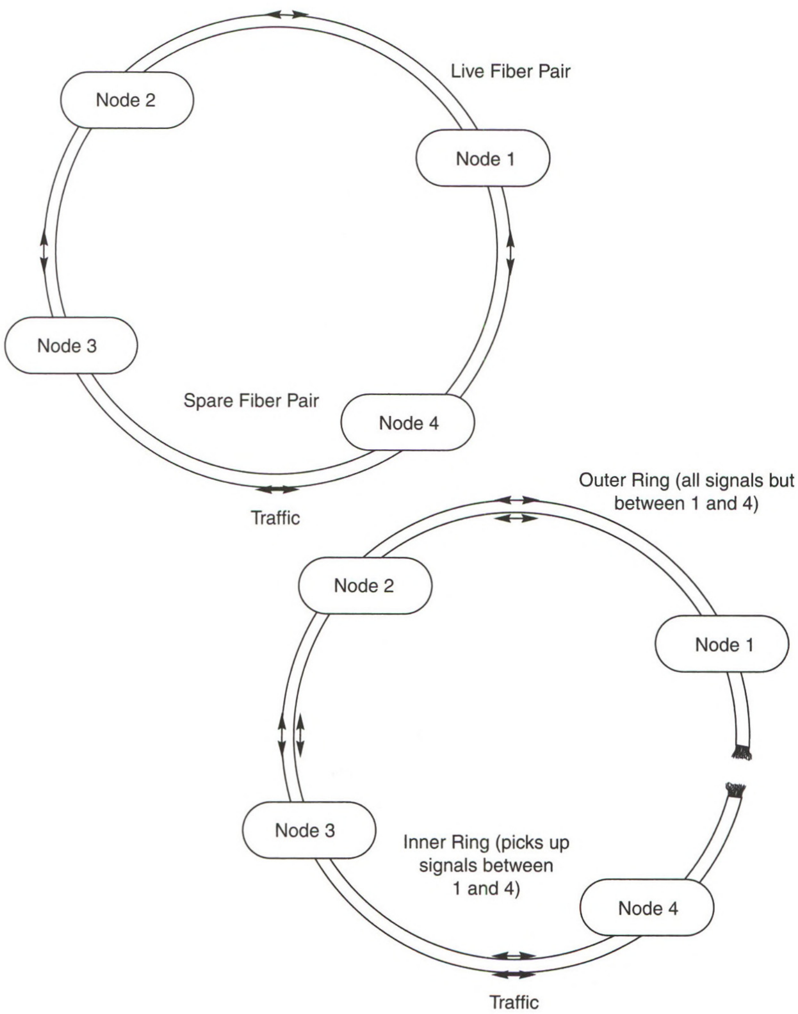


FIGURE 16.5
Protection switching. In case of a fiber break, switches at nodes 1 and 4 redirect traffic between those nodes over the spare fiber pair.

for a World Series or Superbowl. Optical switches are rarely used for *circuit switching*, making temporary connections such as those needed for a telephone call, because fibers handle much larger blocks of information.

Optical switching is still a young technology, and both hardware and applications are evolving. Most nonprotection switching is still electronic, but optical switching is coming, because it can manage higher-capacity transmission. Let's take a more careful look at the functional requirements for various types of switches.

Protection switching sends signals through a backup fiber.

Protection Switching

Protection switching is a simple but vital function. In case of a cable break or equipment failure, the network must redirect signals along a different path that will bypass the failure.

Ideally this should be done automatically in a small fraction of a second, so no telephone connections over the broken link are likely to be dropped. Some data will be lost, but protocols exist to retransmit the data.

Signals can be switched to a backup route at the transmitter output or at a node somewhere along the system. The equipment required is relatively simple. Something must detect the failure and command the switch to divert its signals along the backup fiber. Standard protection switches have two possible outputs, the main fiber and the backup. Their job is to sit and wait. Technicians may test them, but they're not used regularly and repeatedly. If there is a failure, the switch typically will be reset after repairs. This technology is common, and is part of an important telephone-industry standard called *SONET*, which you will learn about in Chapter 20.

Remote Provisioning and Reconfiguration

Provisioning is the changing of network configuration to alter the services delivered to customers, or to provide new services. Traditionally it has been done manually, but now there is much interest in *remote provisioning*. This is a robotic equivalent of sending a technician to a remote site to rearrange cables. The goal is to save money and help telecommunications companies manage their networks more efficiently. Remote provisioning is like going to your basement to set switches when you want to move a phone in your home. That analogy shows both the appeal and the difficulty—switching in new phone lines would be easier than stringing new wires, but you would have to install extra equipment to make it work.

Provisioning changes network configurations to deliver new services.

Provisioning schedules are comparatively leisurely. If you want a new phone line, it doesn't have to be switched on in seconds. However, the operation usually is more complex than protection switching. Remote provisioning is still rare, but it's being designed into new equipment.

Cross-Connects and Circuit Switching

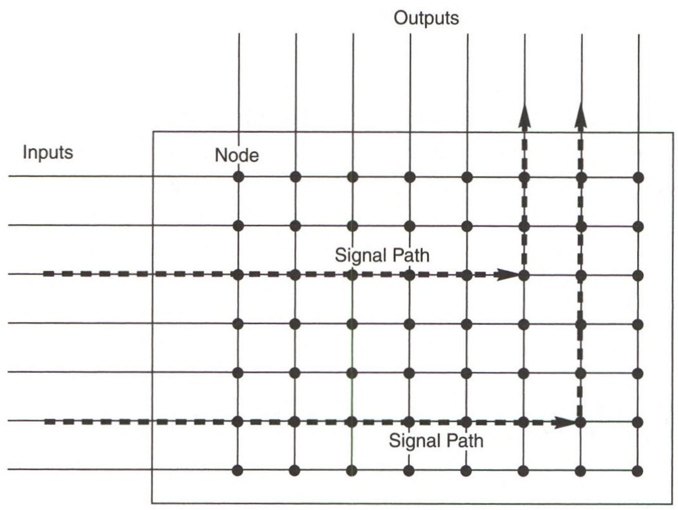
Directing signals among many possible users is a more complex task than protection switching. Figure 16.6 shows the basic idea. Signals must be directed from any of N possible inputs to any of M possible outputs. Switches that perform this task are called *cross-connects* or *switching fabrics*. They perform the same function as the old-fashioned telephone operator who sat at a switchboard plugging pairs of wires into sockets that led to different telephone lines. Monstrous banks of electro-magnetic switches did the same task a generation or two ago; now special-purpose electronic computers lie at the heart of telephone switching offices.

Cross-connects make connections among multiple inputs and outputs.

Optical cross-connects are just beginning to appear in the core of the telecommunication network, where they can transfer high-speed optical signals among input and output fibers. So far, most optical cross-connects can handle only a limited number of inputs and outputs, such as 8×8 switches, with 8 inputs and 8 separate outputs. Optical cross-connects have been demonstrated with up to 1000 inputs and outputs in the laboratory, and commercial versions are in development.

Although it is simplest to think of optical cross-connects as giant-scale versions of switchboards, that is not a very accurate view. Nobody today makes the equivalent of phone calls

FIGURE 16.6
Optical cross-connect.



that stream 10 Gbit/s between two end terminals. The only important uses of optical cross-connects are for load management, to deliver capacity where it is required.

WDM and Optical Switching

WDM channels may be switched together or separately.

So far, we have not considered how many optical channels are transmitted through each fiber. Wavelength-division multiplexing is an important issue in optical switching because different applications require different treatment of optical channels. Some applications require switching all optical channels carried by a fiber in the same way; others require that the optical channels be separated and switched independently.

All optical channels carried by the fiber need to be redirected for protection switching; the standard approach is to simultaneously switch them all to a backup fiber. Switching of all optical channels also may be needed when directing large volumes of traffic; for example, transmitting a large volume of traffic through a series of major switching nodes in a long-distance network. Network managers may organize transmission so one fiber carries signals from New York to Cleveland, which are then switched to another fiber for transmission from Cleveland to Chicago. A separate fiber from New York may carry signals that the Cleveland switch directs to Detroit. Simultaneously switching multiple channels in the same fiber simplifies switch operation.

On the other hand, traffic management often requires redirecting optical channels that arrive through the same fiber into several different fibers. For example, another fiber may carry signals from New York for distribution to other cities in Ohio; that is, one wavelength may go to Toledo, another to Akron, a third to Columbus, and a fourth to Cincinnati. In that case, a demultiplexer would separate the WDM signals from New York, then the switch in Cleveland would process them separately.

Redirecting individual wavelengths requires first separating the wavelengths. Depending on the configuration, this may require either isolating one wavelength with an add-drop multiplexer, or completely demultiplexing all the wavelengths.

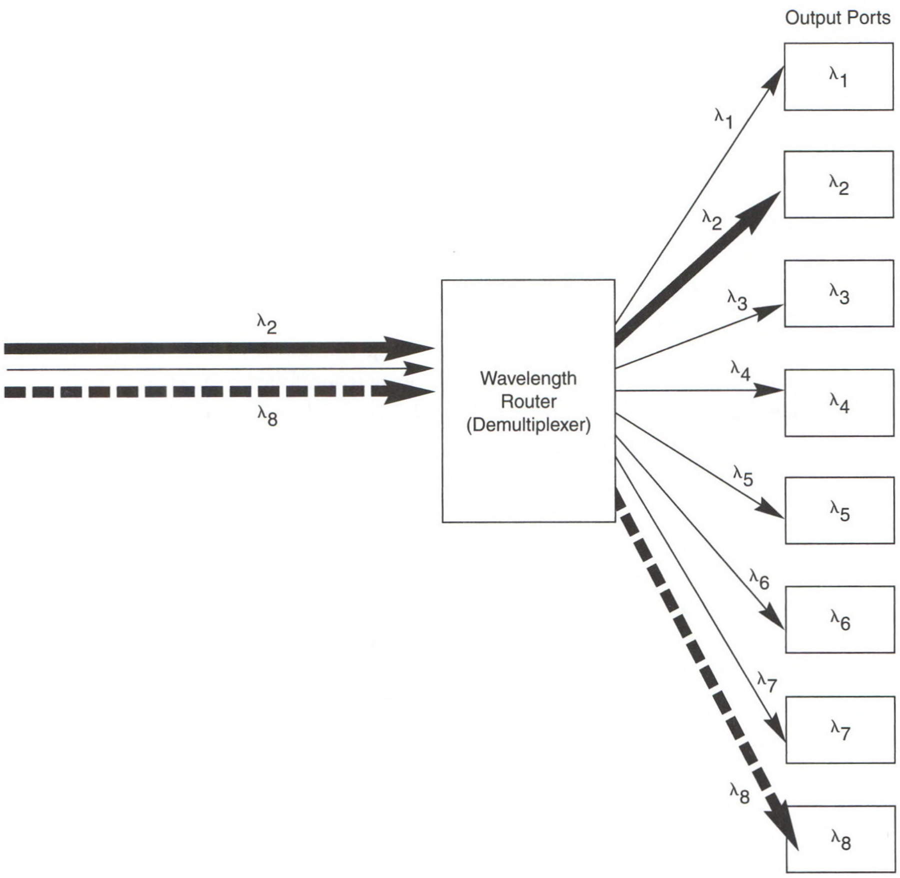


FIGURE 16.7
Wavelength router directs input signals by their wavelength.

Wavelength Routers

One type of WDM switch deserves special mention—the *wavelength router.* Essentially a wavelength router is a special-purpose demultiplexer that directs optical channels to different destinations, depending on their destination. You can think of it as a conventional WDM demultiplexer with fixed output ports. It gets its name from the fact that it routes input signals to their destinations based on their wavelength, as shown in Figure 16.7. Any input signal at λ_2 is routed to port 2, while any input signal at λ_8 is routed to port 8. If you switch the wavelength, you switch the output port. Although present applications are limited by the need for wavelength converters, wavelength routers can provide a distinct function.

A wavelength router separates signals by wavelength.

Note that wavelength routers are distinct from Internet routers, as described below.

Switches and Routers

Switches connect circuits. Routers direct data packets based on their headers.

The difference between switches and routers is an important one in telecommunications, but is easy for newcomers to misunderstand. Although both switches and routers direct signals, they do so in different ways and operate on different kinds of signals.

So far this section has concentrated on switches and switching. Originally, switches made physical connections between electrical circuits, like a wall switch connects a light fixture to an electric power line, turning on the light. Old-fashioned electro-mechanical switches made physical connections between the wires running from your telephone and the wires running to your neighbor's phone.

Circuit-switched systems reserve dedicated channels.

Today, most switching is electronic, with solid-state circuits making connections. Once calls are digitized, your call does not have a whole wire (or fiber) to itself, but it does have a fixed time slot in the series of pulses being transmitted. Engineers still call this connection a *circuit* (or sometimes a *virtual circuit*), although it is not a set of wires dedicated to your conversation. Such circuit-switched systems reserve a guaranteed capacity for each call. It's functionally the same as having your own dedicated pair of wires during your entire conversation, always available whether or not you are talking. Your entire conversation follows the same route.

An alternative approach is called *packet switching.* Instead of holding a dedicated channel open for you all the time, you share the system with many other users. The signals you send are divided into data packets, with headers added to indicate their destination. Devices called *routers* read the headers, then decide where to send the packet based on that information and network conditions at the moment. You can think of them as drivers of parcel delivery trucks who read the label (the header) at your door, then decide the best route to take the package to its destination. The Internet is the most familiar example of packet switching.

Note that there are important functional differences between switches and routers. Switches set up a circuit and leave it alone as long as it's carrying signals. When the connection is finished, the switch hangs up and waits for another call. Switches don't pay any attention to the content of the call beyond the initial information needed to make the connection, and monitoring to see that the line is still in use.

Routers have a more complex job. They must read the headers of each and every packet, then direct it to one of many other routers partway to the packet's destination. The packet is likely to go through a series of routers. Each router in sequence reads the header and sends the packet closer to its destination. Like mail sorters, routers may bundle together packets that are going in the same direction, to be sorted and redistributed at their destination. In addition to reading the headers, routers monitor network conditions to establish the best routes for sending data packets.

It's important to remember that circuit switching and packet routing are different operations, with distinct requirements and hardware. Electronics can do both. So far, optical circuit switches are available, but true optical routers are in the research stage.

Transparent versus Opaque Switches

Transparent optical switches let light go straight through; opaque switches do not.

Optical switches can be divided into two broad categories: *transparent* and *opaque.* The names imply the key difference. Optical signals go straight through a transparent switch without being converted into any other form. One example is a mirror that moves back and forth, directing incident light into one of two possible outputs. The same optical signal that enters the switch is reflected from the mirror, and goes out one of the two possible outputs.

In an opaque switch, the signal is converted into some other form before switching. A simple example is a switch that converts the optical signals into electronic form, processes them electronically, then sends the output signals in one of two possible directions. This sort of switch is considered opaque because the light signal does not go straight through it. Even though both input and output signals are in the form of light, the light is converted into some other form in between.

Free-space Optical Switching

Unlike electrical signals, optical signals can travel freely through the air or empty space. This means that optical switches can have internal gaps, unlike electrical switches that must have continuous physical connections so electrons can flow through them.

Signals may pass through free space inside an optical switch.

Free-space optical switching simply means sending signals between points through empty space instead of through optical fibers. For example, a mirror might be tilted to one of several positions, each one aiming a beam striking the mirror in a different direction.

Optical Switching Technologies

Several technologies can be used for optical switching, and more are in development. The essential idea is to move the beam from one point to another. This may be done mechanically by moving an optical component, or in other ways that shift or deflect light without moving parts. The technologies differ in how fast they can redirect a beam, and in how many different directions they can point it. Some can switch a beam between two directions, while others can aim it over a range of angles.

Opto-Mechanical Switches

Opto-mechanical switches redirect signals by moving fibers or optical components so they transfer light into different fibers. (They are considered distinct from the MEMS switches considered below.) Figure 16.8 shows a simple example. The input signal comes through the fiber on the left. A mechanical slider moves that fiber up and down, latching into one of three positions. Each position directs light from the input fiber into a different output fiber. In this design, the slider flexes a short length of the input fiber.

Opto-mechanical switches move fibers or optics to redirect signals.

Many other designs are possible. Instead of moving a fiber, an opto-mechanical switch could move a mirror or lens to focus light into different fibers. The switch could be toggled mechanically or electronically. With precise optics, you can make an optical cross-connect

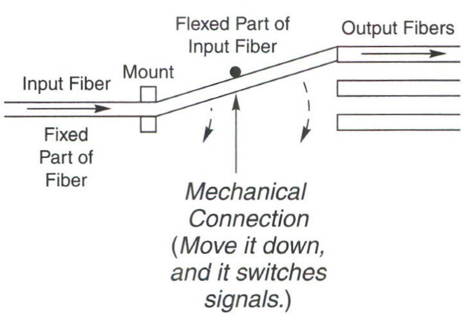


FIGURE 16.8
An opto-mechanical switch.

that focuses light from one of several input fibers onto one of several output fibers. Collimating and collecting optics can focus the beam into the core of the output fiber.

The common element of all opto-mechanical switches is that their operation involves mechanical motion of an optical component. Precise motion is important because fiber alignment tolerances are tight, although large collecting optics can ease requirements. Although opto-mechanical switches are simple in concept, they are far more demanding in practice than electrical switches. Another disadvantage is that telecommunication companies generally prefer to avoid moving parts in our solid-state age.

Nonetheless, opto-mechanical switches have come into wide use because they are the simplest and cheapest optical switches available. They are used mainly for protection switching and other applications where it is vital to be able to switch signals when necessary, but where you hope it isn't necessary very often. They also are used in some instruments.

MEMS Switches

MEMS switches redirect light using tiny moving micromirrors.

Micro-Electro-Mechanical Systems (MEMS) are tiny mechanical structures made by depositing and etching a substrate material in a series of steps. We mentioned MEMS earlier, but they deserve more attention because they are potentially important for optical switching. MEMS structures can be coated with a reflective layer and moved back and forth to deflect light. Although their operation sounds electro-mechanical, that term normally is used only for larger-scale devices, and MEMS are considered a distinct technology.

MEMS technology is adapted from the photolithographic methods of making integrated electronic circuits. Doping and deposition build up a series of patterned layers on a semiconductor substrate—in practice, on silicon. Then some of the material is etched away to leave mirrors supported by posts, as shown in Figure 16.9. Circuits deposited on layers below the suspended mirrors can carry currents, which generate electromagnetic forces that can pull on the mirrors, tilting them. The tilting mirrors scan reflected light across space and can direct beams to output ports. They require about 10 volts to activate, can switch position in microseconds, and can operate for hundreds of millions of cycles.

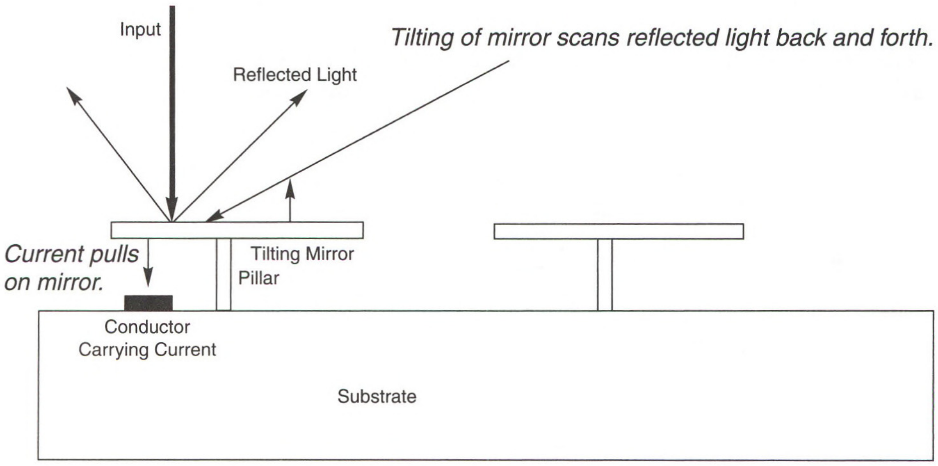


FIGURE 16.9 *MEMS mirrors tilt back and forth.*

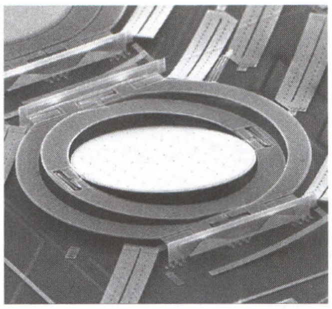


FIGURE 16.10
Two-axis tilting mirror. The center mirror pivots on two axes defined by the two surrounding rings. (Courtesy of Lucent Technologies)

Originally developed for use in displays, optical MEMS have been adapted for switching. Arrays of mirrors are fabricated on silicon substrates. With careful design, complex mirrors can be made to tilt back and forth in two dimensions, so they could scan both vertically and horizontally. Figure 16.10 shows an example of such a mirror, encircled by a pair of rings that can tilt it in two dimensions.

Such tilting mirror structures can scan over a range of angles, so they can collect light from many distinct input ports and direct it to any of many distinct outputs. This gives tremendous flexibility, but it makes accuracy essential. If the mirrors drift from their assigned positions, the output can go to the wrong port.

An alternative design moves mirrors between two distinct positions, where they latch in place. You can think of them as being in either the "up" or "down" position. If they are down, light goes through their position unchanged. If the mirror is up, it reflects light in a single alternative direction. Because the mirror latches into place, it always reflects light in the same direction, easing the need for alignment.

Some MEMS switches latch into two distinct positions.

Latching structures are somewhat more complex than tilting mirrors, but moving between fixed positions is attractive for some applications. Advocates sometimes call these latching mirrors "digital" MEMS because they have only two positions, the equivalent of "off" and "on." This is a careful choice of words, because it implies tilting mirrors are "analog" and thus imprecise and obsolete.

MEMS technology enjoyed a boom during the telecommunications bubble, but suffered badly in the aftermath. Many problems came from overpromotion of business prospects, but technical issues also remain to be resolved, including the long-term performance of MEMS optical switches.

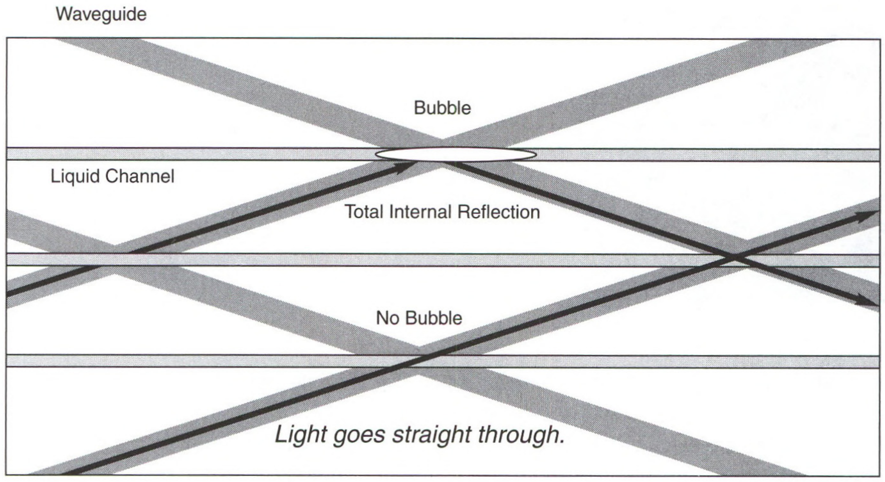
Bubble Switches

Bubbles that move back and forth in liquid guides also can serve as an optical switch. In these devices, two grids of planar optical waveguides cross each other on a substrate, as shown in Figure 16.11. These waveguides have a higher refractive index than the substrate, so they guide light across the flat device. Channels containing a liquid with the same refractive index as the waveguides cross through the junction points of the waveguides.

Bubbles moving back and forth in liquid guides can switch light by total internal reflection.

As long as liquid fills the channel at the junction point, the light sees a continuous waveguide and goes straight through the junction. This changes when a bubble moves into the junction point. The refractive index in the bubble is much lower than that in the liquid,

FIGURE 16.11
Bubble switch.



and the waveguides cross at a sharp angle, which is beyond the critical angle for total internal reflection. When the bubble is in place, it causes total internal reflection, diverting the light down the other waveguide, as shown in Figure 16.11.

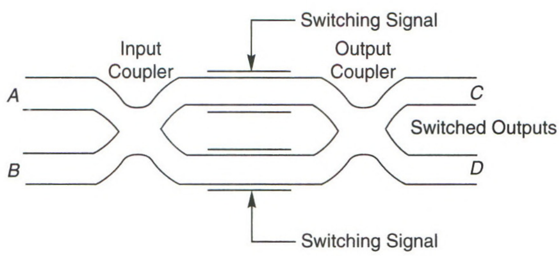
The same techniques used to control ink-jet printers can move bubbles back and forth in the channels, which are sealed to keep the liquid from escaping. The bubbles can be formed by vaporizing small amounts of the liquid, with expansion regions left in the liquid channels to allow for changes in volume. Bubble switches have no mechanical moving parts, although the liquid does move. The technology is considered promising for optical cross-connects but is still young.

Electro-Optical Switches

Voltages applied to planar waveguide channels switch signals in electro-optical switches.

The electro-optic waveguide technology used for the electro-optic modulators described earlier in this chapter also can be used to make a solid-state optical switch with no solid or liquid moving parts. To make a switch, the single input waveguide is replaced by a pair of input guides that meet in a 2×2 coupler connected to the active section. Then the single output of the two parallel guides in the active section is replaced by a 2×2 coupler splitting the signal between a pair of output guides. Figure 16.12 shows the idea.

As in the modulator, operation depends on applying a voltage to one or both of the parallel electro-optic guides in the active section. This changes the refractive index, delaying the phase of light in one waveguide relative to the other. Changing the relative phase of the output signal from the two guides by 180° switches it from one output port to the other. This can switch a single input from one output channel to the other. If separate input signals are entering the top and bottom ports, a 180° phase shift can swap the two between different outputs, as shown in Figure 16.12. If you merely want to switch a signal off and on, you can switch it off by directing the light to a port that goes nowhere. The result is a solid-state switch with no moving parts and a very quick response time. The only changes are in the drive voltage. Normally electro-optical switches are made of lithium niobate, because applying a voltage across the waveguide causes a large change in refractive index.



Switching Signal	Connections
V_1	A–C, B–D
V_2	A–D, B–C

FIGURE 16.12
A 2 × 2 electro-optic switch.

This approach works well for switching one or two ports, but more complex switching configurations require cascading a series of waveguide switches. A 1 × 4 waveguide switch requires a cascade of three 1 × 2 switches, with the first switch providing the inputs for the other two, which have a total of four outputs. An 8 × 8 switch would require a total of 64 switching elements. Although this sounds cumbersome, it has been effective in meeting actual requirements for optical switching, which proved far more modest than market analysts had expected. Waveguide electro-optic switches enjoy two major advantages—a well established technology and all solid-state operation, with no moving parts.

Thermo-Optic Switches

Thermo-optic switches work by using interference effects produced by changing the refractive indexes of a pair of parallel arms coupled at both ends. They can be made either as waveguides or as discrete devices. In thermo-optic devices, heating changes the refractive index of one arm, shifting the relative phase of the light to switch the output between two ports. Thermo-optic switches use different materials than electro-optic switches, but the optical principles are the same.

Thermo-optic switches change refractive index by heating.

Thermo-optic switches are slower than electro-optic switches, with response time of milliseconds. However, this is adequate for most types of optical switching, and they are widely used. They are also solid-state devices, and are less expensive than electro-optic switches.

Liquid-Crystal Switches

Another switching technology, long used in optical displays, is liquid crystals. Liquid crystals get their name because their large molecules tend to orient themselves in the liquid phase, although they do not form a fixed lattice like a solid crystal. This molecular alignment can polarize transmitted light. The types of liquid crystals used in displays have another important property—applying an electric field can change their orientation, and thus change their effect on the polarization of transmitted light.

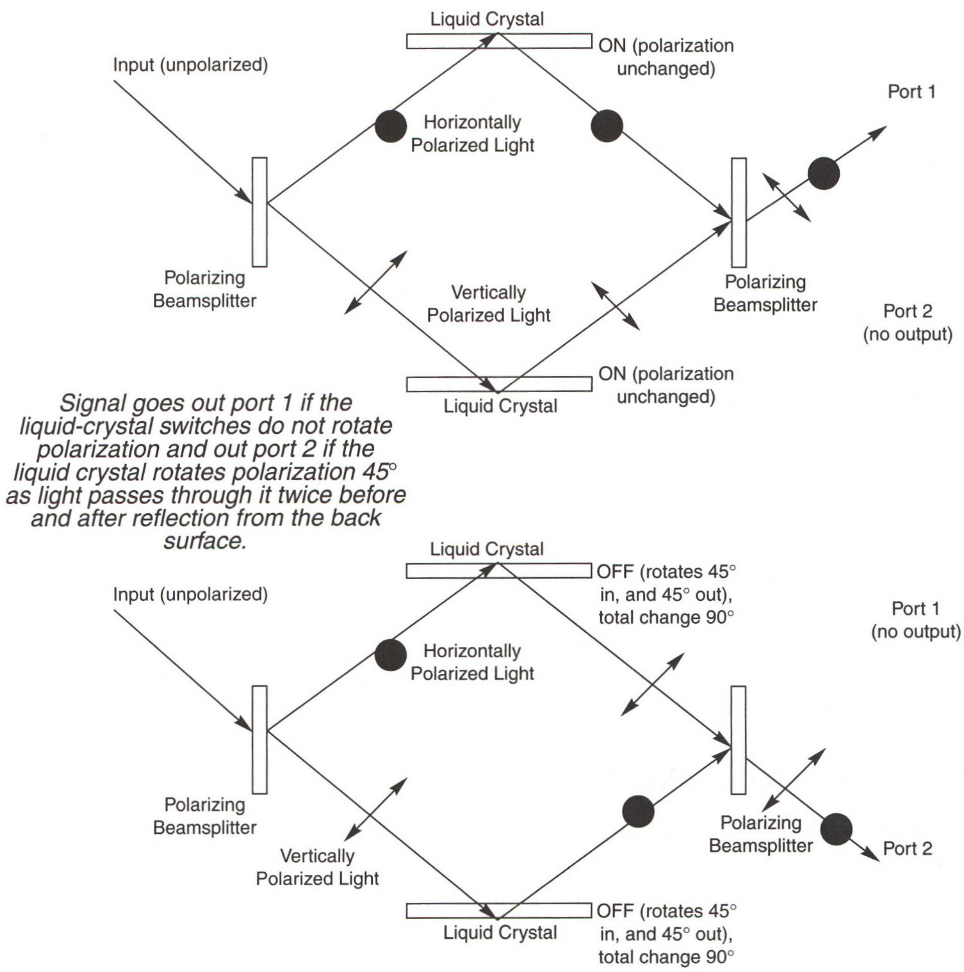
Liquid-crystal switches work by changing light polarization.

For displays or switches, liquid crystals are sandwiched in a thin layer between two parallel glass plates with electrodes applying a voltage across the liquid. The voltage switches between two states, typically one that rotates the polarization, and one that leaves the polarization unchanged. Adding a polarizer makes the device function as a switch or display.

For example, suppose a vertical polarizer is put on the top of a liquid crystal device, so light passes through the polarizer before entering the liquid crystal. Applying a voltage then rotates polarization 45° as the light passes through the liquid crystal layer when it is reflected by the rear surface, and rotated another 45° as it passes back through the liquid crystal. Thus the light exiting the liquid crystal has rotated 90° to be horizontally polarized, and is blocked by the polarizer. Those regions would look dark on a liquid crystal display.

The switch shown in Figure 16.13 works in a similar way. Input light is separated into its two polarizations and reflected off a liquid crystal plate. In this case, the liquid crys-

FIGURE 16.13 *Liquid-crystal switch.*



tal rotates polarization 45° when the voltage is off, but does not affect polarization when it is on. As a result, the reflected light has different polarizations when the voltage is off or on. Polarizing optics deflect that light in different directions, depending on its polarization, so the light emerges from different ports depending on the voltage applied to the liquid crystal.

Wavelength Switching and Conversion

So far we have assumed that all the switching is between fibers, with any WDM signals all being switched together. Although that's usually the case for most optical switching (other than at the ends of a system), the switching process can get considerably more complex in some situations.

One case is a variation on the optical add-drop multiplexer described in Chapter 15. Sometimes called a *reconfigurable optical add-drop multiplexer*, this device is actually a switch that selects one or more wavelengths to drop at a particular location. Actually two steps are involved—selecting the wavelength, then switching it. In practice, this can be done by demultiplexing the signal and routing the wavelengths separately to switches that select which optical channels will be dropped, as shown in Figure 16.14. Other approaches in development would switch a single wavelength without having to demultiplex the entire signal.

Switching of an individual optical channel also can create the need for converting the signal on that optical channel to another wavelength for transmission through a different WDM fiber system. You can think of this conversion process as shifting the signal between different lanes on the optical information highway.

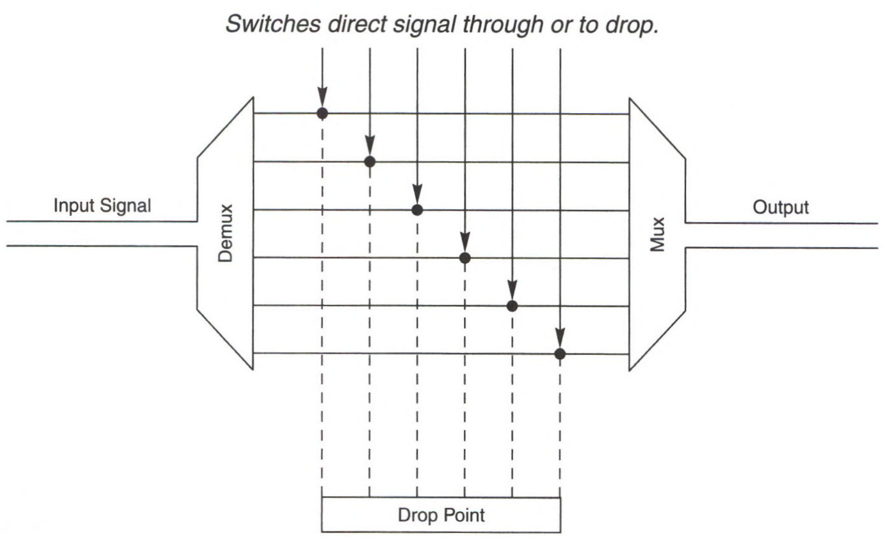


FIGURE 16.14 *Switching at a reconfigurable add-drop multiplexer.*

You learned about wavelength conversion in Chapter 12. There are two main approaches. One is opto-electro-optical (OEO) conversion, in which the optical signal is converted to electronic form to drive a laser transmitter emitting at the desired wavelength. That's a brute-force approach, but it's easy to implement, and it's done quietly today within electronic switches at the end points of transmission lines. OEO conversion also can be made quite flexible by using tunable lasers in the transmitter, so the output wavelength can be selected. All-optical wavelength conversion is possible, but the technology is still in development and is not widely used.

Both wavelength switching and wavelength conversion are expected to become important technologies as the telecommunications network evolves toward a future all-optical network. We aren't there yet, however, and today those functions are largely handled by converting optical signals into electronic format.

Integrated Optics

Integrated optics combine functions in a single monolithic device.

In Chapter 6 you learned about passive planar waveguides that guide light in ways similar to optical fibers but are rectangular in cross-section. Planar waveguides can be integrated on the same monolithic substrate with other flat components—such as semiconductor lasers—to make *integrated optics* that can perform multiple functions. The concept has been around since the late 1960s, when it was proposed as an optical counterpart to integrated electronic circuits. However, optical integration has proved considerably more difficult than electronic integration, and so far has found only limited applications.

Some planar waveguide components are already well developed, including the electro-optic modulators and switches described earlier in this chapter. Edge-emitting semiconductor lasers and semiconductor optical amplifiers also are planar waveguide devices, because light is guided through a narrow stripe in their thin active layer. Yet the degree of integration is modest compared to electronics. One example is the combination of an electro-absorption modulator with a semiconductor laser on the same substrate. Another is the arrayed waveguide grating described in Chapter 15.

Integrated optics is widespread in the laboratory.

Integrated optics activity is widespread in the laboratory, pushed by efforts both to achieve high performance and to reduce costs. Arrayed waveguide gratings have been integrated with other components so that WDM signals can be demultiplexed, individual optical channels modified, and the signals then multiplexed for further transmission. Many advanced functions such as wavelength conversion have been demonstrated with integrated optics. Mass production of simple integrated optics is promising for reducing system and component costs.

A separate class of devices, sometimes called *integrated optoelectronics*, is being developed to reduce costs, particularly of transmitters and receivers. As the name suggests, they integrate electronic as well as optical functions. Examples include combining detectors and amplification circuits, or drive circuits with light sources. Some of these devices are not true monolithic circuits made on a single substrate, but hybrid circuits that bond together two chips made of different semiconductors, one for the optics and the other for the electronics.

What Have You Learned?

1. Active components change signals. They typically draw power from an external source. Modulators and switches are important examples.
2. In high-performance transmitters, an external modulator produces the output signal by modulating the intensity of a continuous beam from the laser source.
3. Electro-optic modulators rely on electric fields to change the refractive index of lithium niobate in a planar waveguide. This delays the phase of light in one of two parallel guides, causing interference, which modulates light intensity.
4. Electro-absorption semiconductor modulators are reverse-biased diodes. Applying a drive current causes them to absorb light at the laser wavelength. Laser and modulator can be integrated on the same chip.
5. Optical networks require optical switches to direct and process signals.
6. Protection switching sends signals through a backup fiber in case of failure. Provisioning changes the services delivered over telecommunication lines.
7. Cross-connects can connect any of multiple inputs to any of multiple outputs. A telephone switch is a good example.
8. The WDM channels carried in a single fiber may be switched separately or collectively.
9. A wavelength router directs input signals according to their wavelength. The same wavelength always goes to the same destination.
10. Switches connect circuits or reserved channels. Routers direct data packets based on their headers. The standard telephone network is circuit-switched. Internet data is transmitted by packet switching and directed by routers.
11. Opto-mechanical switches move fibers or bulk optics to redirect signals.
12. MEMS are micro-electro-mechanical systems made by etching tiny mechanical structures from a semiconductor. They include tiny micromirrors, which can be moved to switch optical signals. MEMS mirrors may tilt over a continuous range, or latch into distinct positions.
13. Bubble switches direct signals by moving bubbles back and forth in liquid guides to the junction points of planar waveguides. The bubbles redirect signals by total internal reflection.
14. Electro-optical and thermo-optical switches change the refractive index of planar waveguides, causing interference, which switches the signal between a pair of output ports.
15. Liquid crystal switches affect the polarization of light; they are used together with polarizers to switch light.
16. Variable or dynamic filters change attenuation too slowly to modulate an optical signal.

17. A reconfigurable add-drop multiplexer switches individual optical channels in a WDM system. Wavelength conversion may also be needed in WDM systems.
18. Integrated optics combine multiple functions. Only modest integration is used in commercial components, but more extensive integration is in development.

What's Next?

Chapter 17 describes optical measurement techniques.

Further Reading

J. Capmany et al., eds., special issue on "Arrayed Grating Routers/WDM Mux Demuxs and Related Applications/Uses," *IEEE Journal Selected Topics in Quantum Electronics 8,* (November/December 2002)

K. Okamoto, *Fundamentals of Optical Waveguides* (Academic Press, 2000).

Rajiv Ramaswami and Kumar N. Sivarajan, *Optical Networks: A Practical Perspective* (Morgan Kaufmann, 2002)

Questions to Think About

1. An external modulator with a 20-dB extinction ratio modulates the output of a 1-mW laser. The signal then passes through 20 km of fiber with loss of 0.5 dB/km. Neglecting other losses, what are the power levels at the detector when the light is off and when it is on?
2. What are the power levels in Question 1 if the external modulator has insertion loss of 3 dB?
3. What are the power levels for Question 1 if the external modulator has 3-dB insertion loss and an extinction ratio of 10 dB?
4. One important issue in switch design is the number of elements required to switch the signals. Suppose you have a simple cross-connect switch such as the one shown in Figure 16.5, with a single switch element at each node, which either transmits or reflects the beam. If you have 10 inputs and 10 outputs, how many switching elements do you need? What if you have 100 inputs and 100 outputs?
5. A tilting-mirror switch can reflect the light input from a single input port to any of N output ports. With this design, how many switching elements do you need for a 10×10 switch? A 100×100 switch? Assume the tilting mirror can point the beam at as many output ports as needed.
6. How does the bubble switch shown in Figure 16.11 scale? What number of bubble-waveguide intersections do you need for an $N \times N$ optical cross-connect?

Chapter Quiz

1. What phase shift do you need to cause destructive interference between two coherent beams of light, canceling them out?

a. 0°

b. 45°

c. 90°

d. 180°

e. 360°

2. What material is used in electro-optic modulators and switches?

a. lithium niobate

b. gallium arsenide

c. indium phosphide

d. silica on silicon

e. any of the above

3. How should an electro-absorption modulator be biased to block light transmission?

a. No bias is required; it is normally opaque.

b. reverse bias

c. forward bias

d. It must be biased in the same direction as the integrated laser light source.

4. Telecommunications customers use provisioning switches for

a. backup during repairs of a failed transmission line.

b. making temporary circuit connections to direct telephone calls.

c. changing services provided to customers.

d. routing data packets over the Internet.

5. Operation of an optical cross-connect is analogous to

a. fuses that block electrical power transmission if a circuit overloads.

b. a telephone switchboard that makes connections between callers.

c. a fleet of trucks delivering parcels over the best available routes.

d. municipal water services that pipe water to all homes and businesses.

6. A wavelength router

a. directs incoming signals to outputs according to their wavelengths.

b. is an Internet router able to process WDM signals at multiple wavelengths.

c. is an Internet router that can process optical signals at only one wavelength.

d. is an optical cross-connect that converts optical signals to different wavelengths.

7. The difference between switches and routers is

a. switches are mechanical and routers are electronic.

b. switches are optical and routers are mechanical.

c. switches connect circuits and routers direct packets.

d. switches direct packets and routers reserve channels.

e. just a difference in marketing buzzwords.

8. What kind of switch converts an optical signal to electronic form, then uses the electronic signal to drive another optical transmitter?

a. transparent

b. opaque

c. opto-mechanical

d. electro-optical

e. bubble

9. An opto-mechanical switch

a. uses light to mechanically move an electrical switch.

b. mechanically moves a fiber, mirror, or lens to redirect optical signals.

c. mechanically moves an electronic switch to redirect optical signals.

d. uses light to mechanically move an optical switch.

e. none of the above

10. What type of optical switch can direct light across a range of angles to any of the many possible output ports?

a. an electro-optical switch

b. a pop-up MEMS switch that latches in one of two positions

c. a tilting-mirror MEMS switch

d. a bubble switch

e. a liquid-crystal switch

11. How could you assemble a 1×8 electro-optical switch?

a. by dividing one input waveguide into eight optical waveguides

b. by moving one input fiber to connect with one of eight output fibers

c. by tilting a mirror to one of eight possible positions directing light to different outputs

d. by cascading a series of seven 2×2 switches, with the two outputs of the first going to inputs of two separate second-stage switches, and the four outputs of those switches going to inputs of four final-stage switches

e. It's impossible.

12. What is the key difference between a MEMS switch and an opto-mechanical type?

a. The MEMS switch has no moving parts.

b. Opto-mechanical switches have only two possible outputs.

c. MEMS switches are miniature monolithic devices with movable elements.

d. None of the above

13. Which type of switch operates by changing the polarization of light?

a. MEMS

b. opto-mechanical

c. bubble

d. liquid-crystal

e. electro-optical

14. Which of the following is not an application of optical switches?

a. protection switching around a damaged fiber

b. changing transmission lines to serve a new customer

c. redirecting signals at the terminal point of a cable

d. balancing transmission load among several possible routes for a telecommunications carrier

e. routing Internet packets