CHAPTER

15

Wavelength-Division Multiplexing Optics

About This Chapter

Wavelength-division multiplexing (WDM) multiplies transmission capacity by allowing a single optical fiber to carry separate signals at multiple wavelengths, but that benefit comes at a cost in complexity. Additional optical components are needed to combine and separate optical channels at closely spaced wavelengths, and to process the signals as they are transmitted. Specific requirements vary with system design, and several technologies are in use.

This chapter first outlines the basic requirements, then explains how these requirements relate to the operation of WDM systems. Then it covers specific technologies, their operation, and their capabilities. The chapter introduces the important concepts of wavelength-selective optical filtering, and describes the types of devices that can perform it. You will recognize a little overlap with the couplers and attenuators described in Chapter 14, which can be adapted for wavelength selectivity. The current chapter concentrates on passive technologies like those in Chapter 14, but does mention some active technologies that serve similar purposes in "dynamic" versions of passive components. Chapter 16 will cover switching, modulation, and other "active" technologies.

WDM Requirements

At first glance, wavelength-division multiplexing looks simple; it's easy to shine light of many different colors into an optical fiber. The hard part seems to be the *demultiplexing*, when you have to separate the output signals by their wavelength. Unfortunately, reality is not quite that simple. Demultiplexing is a more difficult task, but care does

Demultiplexing is harder than multiplexing.

need to be taken in multiplexing, to control background noise that might otherwise be introduced into the fiber. Other types of processing also require some type of wavelength selection.

There are a number of basic requirements for WDM, which often differ in degree:

- *Wavelength multiplexing* or combination, which must transmit the desired signal while blocking noise at other wavelengths, which might interfere with other optical channels.
- *Wavelength demultiplexing*, to isolate individual optical channels for detection or further processing.
- *Add-drop multiplexing*, often called "optical add-drop multiplexing," which separates and combines only a few wavelengths from many wavelengths transmitted by a system.
- *Wavelength separation*, typically to isolate a signal wavelength from a pump wavelength, as in an optical amplifier.
- *Wavelength-selective processing*, such as attenuating signals at some wavelengths to balance the strength of all optical channels in a system. This may be static or dynamic.
- *Wavelength conversion*, to change a signal from one wavelength to another. (See Chapter 12.)
- *Wavelength switching*, to redirect signals at one or more wavelengths while transmitting others unchanged. (See Chapter 16.)

The specific requirements depend on system properties such as the number of channels, the spacing between them, the distance spanned, the amplification required, and the system configuration. Requirements differ greatly between a system that carries eight optical channels between two office buildings 10 kilometers apart, and a network that carries 32 optical channels several hundred kilometers, dropping and adding signals at cities along the way. A few of these requirements are not exclusive to WDM systems, such as separating the pump light from the signal in an erbium fiber amplifier, which could be amplifying only a single wavelength.

Many advanced concepts were never implemented outside the lab.

During the telecommunications bubble, there was much talk of dynamically reconfigured optical networks carrying large numbers of optical channels, which they would routinely switch and convert to different wavelengths. Most of these ideas were never implemented outside the laboratory, and little demand for them seems likely in the near future. We will talk about some of these ideas that may find practical applications, but not in much detail.

WDM Systems

Multiplexers combine optical channels; demultiplexers separate them.

The basic elements of a WDM system are shown in Figure 15.1. Optical signals from eight transmitters at separate wavelengths are combined in a *multiplexer* at the left. The signals travel through the same fiber from the multiplexer to an *add-drop multiplexer* in the middle, which extracts one wavelength, λ_4, from the main signal and directs it to a local receiver. It also picks up another signal from the local transmitter at the same wavelength, called λ_{4*}, to show it is a different signal.

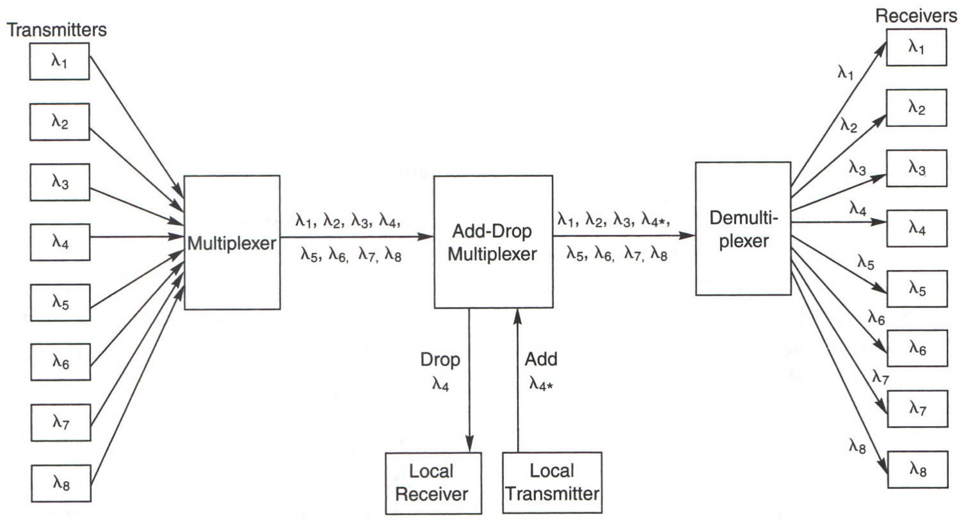


FIGURE 15.1
A WDM system.

At the right side, the eight signals are split in a *demultiplexer* and routed to separate receivers, one for each wavelength. As you learned in Chapter 11, receivers are color-blind in the sense that they respond in the same way to all wavelengths they can detect. This means that the signals must be completely separated, because any stray light at a different wavelength will show up as noise in the receiver output. If some light from the signal at λ_5 reached Receiver 6, the receiver would think it belonged in channel 6, and it would interfere with the actual λ_6 signal.

You can think of the multiplexer and demultiplexer as mirror images, but they are not identical. The multiplexer takes separate wavelengths and combines them, and the demultiplexer takes combined wavelengths and separates them. Key operating considerations differ between the two. Multiplexers should have low insertion loss and avoid scattering light back to any of the transmitters. Demultiplexers must reliably separate the optical channels, with low leakage of light from one optical channel into an adjacent channel. In practice, the two devices can be used as mirror images of each other, although sometimes the multiplexers may have wider channel spacing than the demultiplexers to reduce insertion loss.

Demultiplexers must separate optical channels completely, with low crosstalk.

The add-drop multiplexer serves a different function, picking out one or more wavelengths from a combined signal so they can be "dropped" at a location partway along a system. It also can "add" signals transmitted from the midpoint station onto empty channels. In Figure 15.1, it is adding a signal λ_{4*} to replace the signal that has been dropped at the λ_4 wavelength.

The way these system elements operate depends on various factors including the number and density of optical channels, and the topology of the system—that is, how it collects and distributes signals.

Optical Channel Density

WDM optics provide a number of uniformly spaced slots for optical channels, although the system operator may not populate all those slots with transmitters and receivers. The spacing of these slots determines the potential optical channel density. The maximum number of channels that can fit into a given spectral width is the bandwidth divided by the channel spacing:

$$\text{Channel Capacity} = \frac{\text{total bandwidth}}{\text{channel spacing}}$$

System designers can pick any channel spacing they want, but in practice most WDM systems fall into two specific categories based on industry standards:

DWDM channels are spaced 200, 100, or 50 GHz apart.

Dense Wavelength-Division Multiplexing or *DWDM* is based on channel spacing of 200 GHz or less. Normal center-frequency spacings are 200, 100, or 50 GHz, based on a standard grid developed by the International Telecommunications Union. A 100-GHz spacing corresponds to 0.8 nm in the erbium-amplifier band. Most DWDM systems operate in the erbium-amplifier band around 1550 nm, which is used for long-haul, high-capacity transmission.

CWDM channels are spaced 20 nm apart.

Coarse Wavelength-Division Multiplexing or *CWDM* is based on channel spacing of 20 nm across a range from 1270 to 1610 nm, set by the ITU under standard G.694.2. The CWDM standard creates 18 channels across the low-loss window of low-water fibers. CWDM is intended for use in metro networks where transmission distances are at most tens of kilometers and amplifiers are not required.

Note that CWDM spacing is in wavelength units while DWDM spacing is in frequency units. This means that DWDM channel spacing is uniform in frequency across its operating range, but not uniform in wavelength. Likewise, CWDM channel spacing is uniform in wavelength but not in frequency units.

The difference in fiber capacity of these two spacings is dramatic, as shown in Figure 15.2. Forty 100-GHz DWDM channels fit into the 1530–1565 nm C-band of erbium amplifiers.

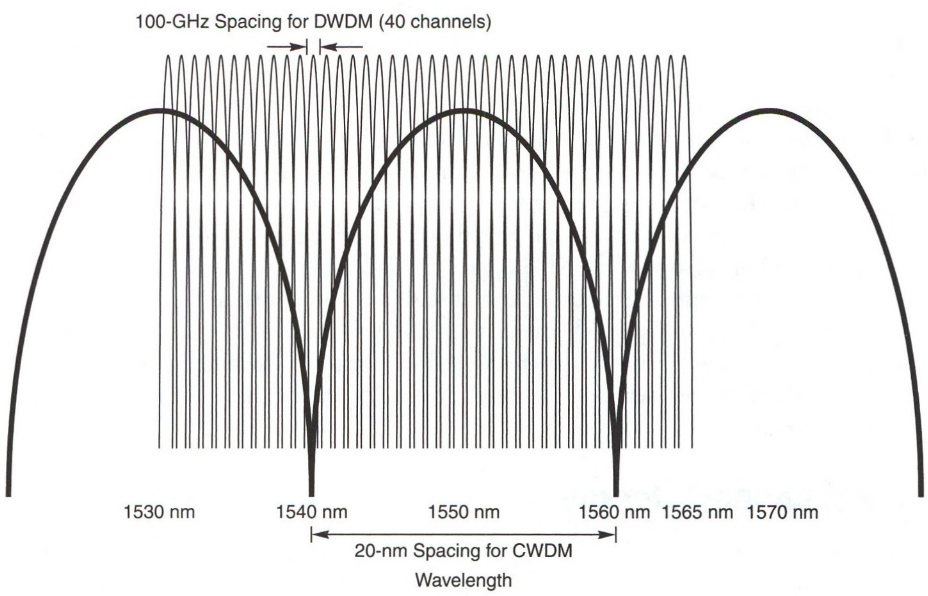


FIGURE 15.2 *Channel spacing in DWDM and CWDM systems.*

Two CWDM channels don't quite fit into the same space; channels are centered at 1530, 1550, and 1570 nm.

Wide channel spacing reduces the costs of multiplexing and demultiplexing optics; it also allows the use of inexpensive uncooled directly-modulated laser transmitters. Narrow channel spacing raises costs, but allows a single fiber to carry more bandwidth, which in practice is more important over long distances or where the number of available fibers is limited.

Channel Separation Requirements

DWDM optics don't isolate channels completely.

Demultiplexing optics should separate optical channels cleanly. Ideally the optics should transmit all light at the center wavelength of the optical channel, but block adjacent channels completely. In practice, DWDM optics have some attenuation at the center of the channel, typically 3 to 5 dB, and adjacent channels are attenuated by 20 to 40 dB, as shown in Figure 15.3. Normally the channels are equally spaced, so the points where the curves intersect match the channel widths or, equivalently, the channel separation. Actual transmission curves depend on the technology used for the WDM optics, and in practice spread out more at the bottom than the simplified curves of Figure 15.3.

The overlap of the transmission curves shows where crosstalk occurs. The crosstalk can be reduced by using optics with spectral width narrower than the optical channel, which reduces the amount of signal transmitted but reduces background noise. The amount of

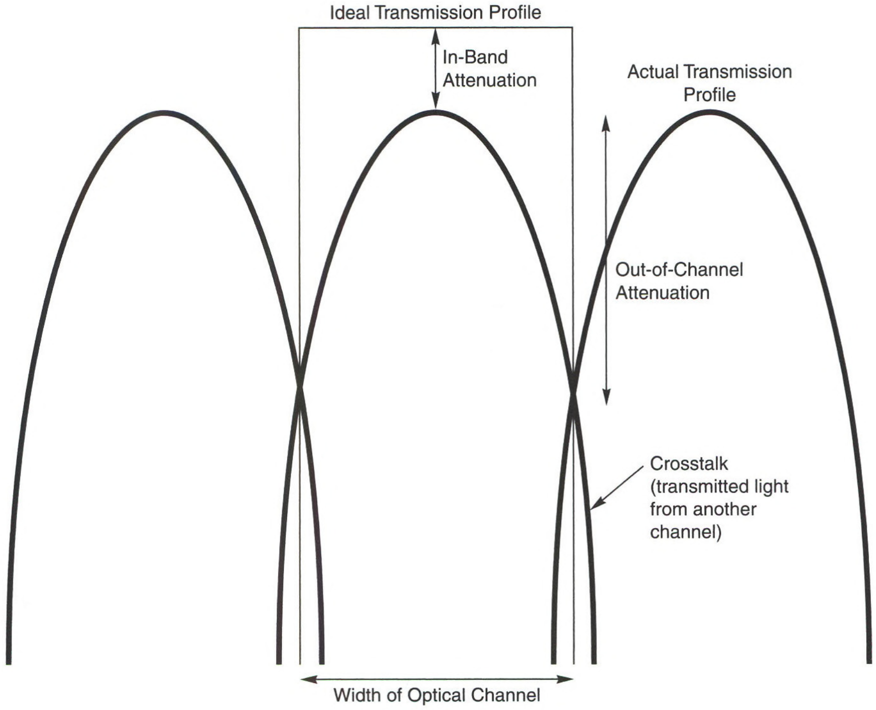


FIGURE 15.3 *Channel isolation in WDM system.*

crosstalk also depends on the range of wavelengths emitted by the transmitter on each channel, which is not shown.

In practice, DWDM systems generally have some empty channels. Some are initially left open to allow later capacity upgrades. Others are in gaps intentionally built into the system to avoid possible crosstalk, such as the gap normally left between C- and L-band erbium amplifiers. Standard C-band amplifiers stop at 1565 nm, and L-band amplifiers don't start until 1570 nm, leaving a 5-nm gap. Some DWDM systems leave similar gaps between blocks of wavelengths, perhaps dropping one or two 100-GHz slots between blocks of eight optical channels.

The wider spacing of CWDM channels eases fabrication of the optics, so crosstalk and channel separation are not as serious concerns as they are for DWDM optics.

Add-Drop Multiplexers

An add-drop multiplexer diverts one or more optical channels, and may add new signals in their place.

A full demultiplexer separates all the optical channels in a fiber, but in many cases you may want to separate only one or two channels from a larger number of channels. This is the job of an *optical add-drop* multiplexer (OADM), like the one shown in the middle of Figure 15.1.

To pick off one optical channel, you pass the light through an optical device that treats the selected channel differently from other channels, such as a wavelength-selective filter. If it reflects the selected channel, it should transmit all other wavelengths; likewise, if it transmits the selected channel, it should reflect all other wavelengths in the system. Figure 15.4 shows how an add-drop multiplexer reflects a selected channel while transmitting other channels, so it can drop one optical channel at a local node while transmitting all other channels. Other optics may be used to add a signal at the same wavelength to replace the dropped channel.

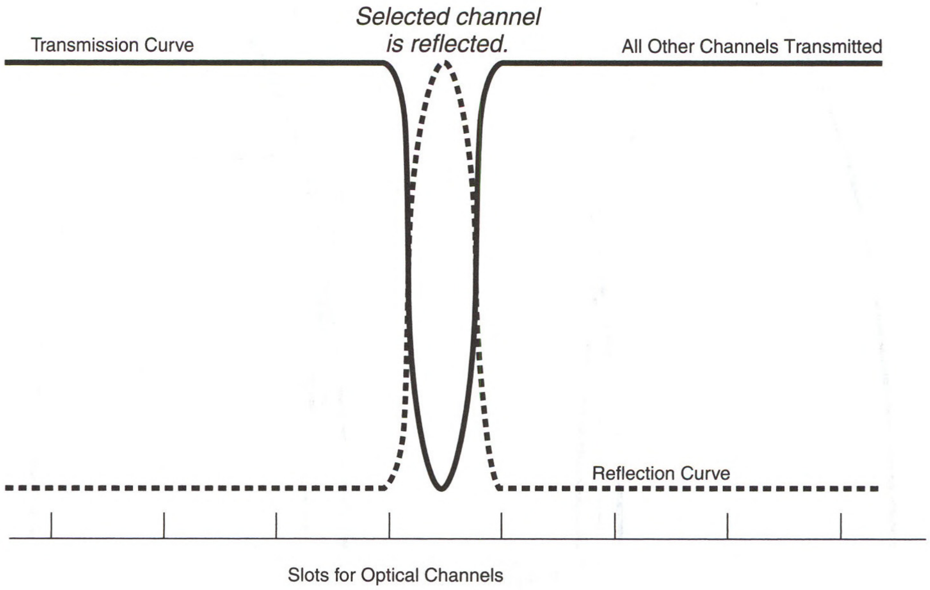


FIGURE 15.4
Add-drop multiplexer reflects one channel and transmits others.

So far we have assumed that an add-drop multiplexer is a fixed device that always adds and drops the *same* wavelengths at the same point. It is possible to build *reconfigurable add-drop multiplexers (ROADMs),* using tunable or active optics. However, they aren't common, and we won't stop to explore their design.

Wavelength Routing

Wavelength routing is another type of optical demultiplexing that works in a different way than the optical demultiplexers we've described so far. Instead of separating optical channels and sending each one to a separate receiver, as shown in Figure 15.1, wavelength routing separates the optical channels and routes them to different destinations. You can visualize this as sending signals at each wavelength to a different town. (As you will learn later, this is not the same as the routing used in Internet transmission.)

A *wavelength router* directs signals according to their wavelength.

Channel Equalization

Not all wavelength-selective optics in WDM systems are used to separate optical channels. Optical amplifiers do not have uniform gain across all wavelengths in their operating bands, so they amplify some channels more than others. This is a minor problem if the system has only one amplifier, but it can build up to a serious problem if the system has a long chain of amplifiers.

Channel equalization optics balance this gain differential by attenuating the wavelengths that are amplified the most, so overall gain is uniform across the system's operating range. Alternatively, they may include supplementary optical amplifiers that amplify the weaker wavelengths.

Advanced Optical Networking

Plans to develop advanced "all-optical networks" came to little when the telecommunications bubble collapsed, but some progress was made on the technology. It's worth noting a few WDM-related ideas that eventually may be implemented in future networks.

- *Optical wavelength conversion* that uses an optical device to shift a signal from one wavelength to another for transmission through other parts of the network.
- *Wavelength tuning* during network operation, so signals could be shifted to other wavelengths remotely by adjusting the transmitter.
- *Dynamic equalization* of optical channel strength across the operating range when the network configuration changes. Adding new optical channels changes the response of optical amplifiers, requiring technicians to adjust them. Dynamic equalizers would measure the change and adjust equalizing filters to compensate.
- *Reconfigurable add-drop multiplexers,* mentioned briefly above, which could automatically adjust themselves, or could be controlled remotely, to adapt to changing transmission needs, such as dropping signals at a new location.
- *Dynamic gain adjustment,* which would automatically adjust gain of optical amplifiers when new optical channels were added to a system.

Optical Filters and WDM

The optical devices most often used to selectively transmit certain wavelengths are called *filters.* The term covers a broad range of devices, including the attenuators described in Chapter 14, and you should understand what they are and how they work. Filters play important roles in WDM systems, although other technologies also may be used.

Sunglasses are a familiar type of optical filter, and like the filters used for WDM, sunglasses come in many varieties. Ordinary gray-green sunglasses are simple attenuators that block a uniform fraction of the light across the spectrum, and don't obviously change the colors of the world. Polarizing sunglasses transmit light of only one polarization, blocking the other polarization. The world doesn't look obviously different through polarizing sunglasses unless you look at certain parts of the sky or surfaces that look unusually bright or dark. Colored sunglasses and some photographic filters make the world look colored because they block other shades. Thus blue or red sunglasses make other objects seem to be those colors.

WDM filters transmit selected wavelengths and reflect others.

In the world of optics, "filter" often is a broad term applied to components that filter out part of the incident light and transmit the rest. Many types, such as photographic filters and most sunglasses, absorb the light they don't transmit. The only places such absorbing filters are used in fiber-optic systems are where it's important to absorb undesired light, such as in attenuators and optical isolators. In WDM systems, the wavelengths that are not transmitted through the filter normally are reflected so they can go elsewhere in the system. Such filters are like mirror shades and one-way mirrors, which reflect most incident light, but transmit enough for you to see through them (if you're looking into a brighter area).

The term "filter" is used a little differently in WDM. Typically it means one specific type of filter, the *interference filter,* which I describe below. Other types of WDM optics such as fiber Bragg gratings *act* like filters, in the sense that they block some light, but they are not considered quite the same. I'll use interference filters as a way to explain the operation of WDM optics, then describe other types of wavelength-selective optics.

Interference Filters

The layers in an interference filter selectively transmit a narrow range of wavelengths, and reflect other light.

Interference filters are made by depositing a series of thin layers of two materials with different refractive index on a flat piece of glass. Alternating layers are deposited of each material. Typically the materials are insulators or dielectrics, which do not conduct electricity, so these filters are sometimes called *dielectric filters.*

The difference in refractive index between the two layers causes reflection at each surface. (The basic phenomenon is the same as the Fresnel reflection that occurs in connectors with an air gap between the fibers.) The more identical pairs of alternating layers, the more the reflection builds up—at most wavelengths.

Light is transmitted only at certain wavelengths, which are selected by the optical characteristics of the layers. As in a resonant laser cavity, the light wave has to make a round trip between the layers in an integral number of wavelengths. Light waves at these wavelengths are in phase with each other, so they add constructively in the transmitted beam. Transmitted wavelengths λ are given by the formula

$$N\lambda = 2nD \cos \theta$$

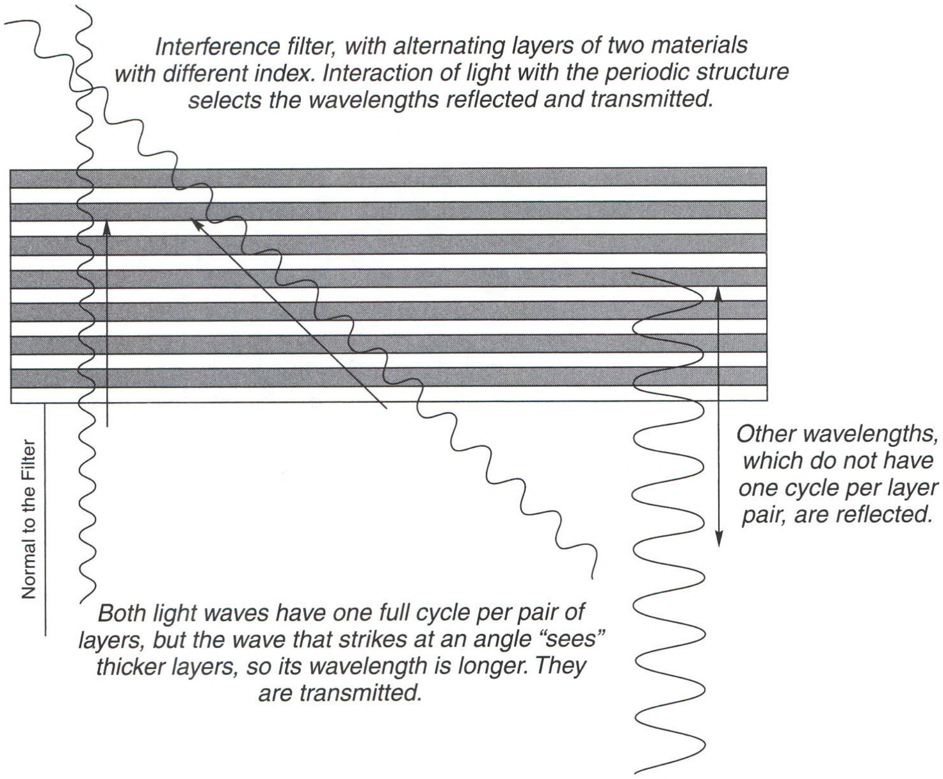


FIGURE 15.5
Wavelength selection in an interference filter.

where N an integer, n is the refractive index of the layer, D is the layer thickness, and θ is the angle the incident light makes to the normal. Figure 15.5 shows how an interference filter transmits light with one wavelength per pair of layers (or one-half wave per layer), and reflects other wavelengths. Note that the wavelength transmitted depends on layer thickness, refractive index, and angle of incidence on the filter.

From an optical standpoint, the transmitted wavelengths are in phase and interfering constructively, so the waves add in intensity. Waves at other wavelengths are out of phase, so they interfere destructively, canceling their amplitude in the transmitted beam. Instead they are reflected.

From the user's standpoint, these effects are analogous to the wavelength selection effects of fiber gratings covered in Chapter 7. However, there is an important difference. Fiber gratings selectively *reflect* a narrow range of wavelengths, while interference filters selectively *transmit* a narrow range of wavelengths. This becomes important in designing demultiplexers, as you will learn later in this chapter.

The precise selection of wavelengths transmitted and reflected, and the shape of the reflection and transmission curves, depend on details of filter design including thicknesses and compositions of the layers, and the numbers of layers in the "stack." Normally the more layers, the finer the resolution, and the narrower the range of wavelengths selected.

The design of interference filters is a well-developed and highly specialized art, and it can produce carefully controlled results. With the right choice of material compositions and layer thicknesses, engineers can coat thin glass plates with interference filters that strongly reflect one wavelength while transmitting almost all the light at nearby wavelengths, so they are widely used in optical multiplexers and demultiplexers.

Although interference filters are considered "bulk optics" because they are discrete components, the filters used in WDM optics are quite small, typically a few millimeters across.

Line, Band, and Cutoff Filters

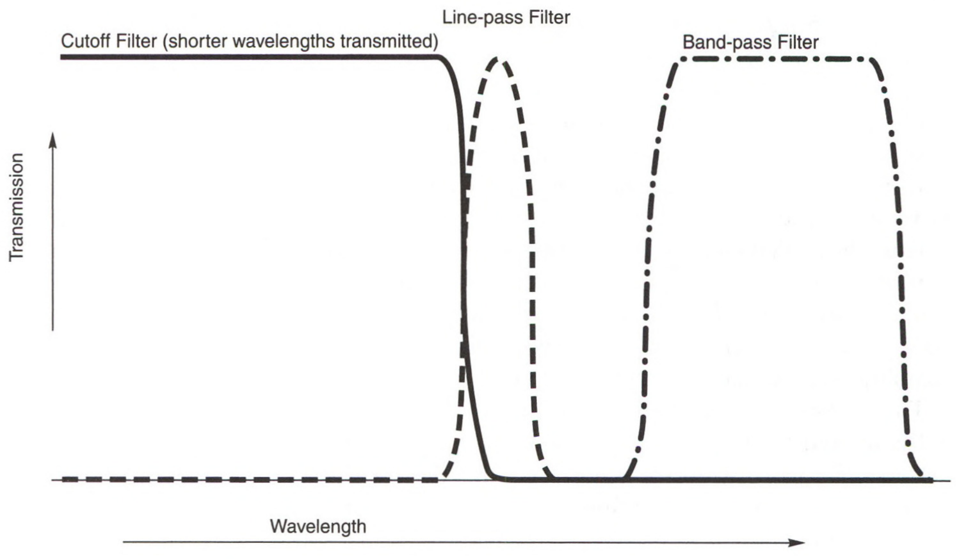
Interference filters can be made with various transmission characteristics by adjusting their composition, the thickness of layers, and the number of layers. Three types of filters important in WDM optics are the *line filter*, the *band filter*, and the *cutoff filter*, Figure 15.6 shows their transmission characteristics.

Line and band filters select a range of wavelengths.

Line and band filters either reflect or transmit light in a selected range of wavelengths. If the range of wavelengths is narrow, they are called *line* filters; an example would be a filter to pick out one 100-GHz optical channel. Filters that select a broader range of wavelengths are called *band* filters; an example would be a filter that selects a 10-nm chunk of the erbium-fiber amplifier band. Line-rejection or band-rejection filters reflect the selected band while transmitting nearby wavelengths; line-pass or band-pass filters transmit the selected wavelengths while reflecting adjacent wavelengths.

Note that you can arrange filters in various ways so one type can serve different functions. For example, a line-pass filter normally transmits one wavelength while reflecting other light. However, you can use a line-pass filter as a line-rejection filter simply by collecting the *reflected* light rather than the transmitted light.

FIGURE 15.6
Transmission of line, band, and cutoff filters.



Cutoff filters are designed to make a sharp transition between transmitting and reflecting at a certain wavelength. For example, a filter designed to separate optical channels directed to C- and L-band erbium-fiber amplifiers would have a cutoff wavelength at 1567 nm, with shorter wavelengths reflected to the C-band amplifier and longer wavelengths transmitted to the L-band amplifier. The cutoff filter in Figure 15.6 transmits short wavelengths but blocks long ones.

Cutoff filters make a sharp transition between transmitting and reflecting at a certain wavelength.

Filter transitions don't have to be sharp; in fact, it's easier to make filters with more gradual transitions because they don't require as many layers. Such gradual cutoff filters can be used to divide widely separated wavelengths, such as the pump band of an erbium optical amplifier and the wavelengths it amplifies.

These filters are made for use at specific wavelengths. Outside that range, their transmission may vary. Thus you can't be sure that a cutoff filter that reflects wavelengths shorter than 1567 nm will also reflect light at 1300 nm unless you have checked its properties at the shorter wavelength.

Equalizing Filters

Earlier we mentioned the need to compensate for the uneven gain of optical amplifiers. This normally is done by equalizing filters, which attenuate the wavelengths that are amplified most strongly. As shown in Figure 15.7, attenuation by the filter offsets the extra gain of the amplifier. The higher the gain, the higher the compensating attenuation. For example, if amplifier gain is 2 dB higher at 1535 nm than at 1550 nm, the filter should transmit 2 dB more light at 1550 nm. The filter may be placed before or after the amplifier, but the idea is the same. After the light passes through both filter and amplifier, the output power should be uniform across the gain band, as shown in Figure 15.7.

Equalizing filters compensate for uneven gain of optical amplifiers.

Fixed and Tunable Filters

The standard interference filters described above always transmit light in the same way as long as light strikes them at the same angle. Such fixed optical filters are fine for many applications, but tunable filters also are attractive for use in instruments or systems that require adjustment. A few different approaches are possible.

Some filters can be tuned to select different wavelengths.

One simple approach is to tilt an interference filter, because the wavelength it selects depends on the angle at which light strikes it. Another is to use a prism or diffraction grating to spread out a spectrum and pick a narrow range of wavelengths from that spectrum. However, neither approach has proved able to meet the stringent requirements of dense wavelength-division multiplexing.

A more complex approach is to move an interference filter that is made so its optical characteristics vary along its length. This approach can meet high-resolution requirements, but requires special filters and mechanical movement of the filter.

A more common approach is the Fabry-Perot interferometer, which is essentially an optical cavity similar to those used as laser resonators, but without the laser medium inside. It consists of two partially transparent mirrors aligned parallel to each other, so light bounces back and forth between them. Normally air fills the space between them. Light bounces back and forth many times once it enters the cavity, so interference effects select wavelengths that

A Fabry-Perot interferometer can be a tunable filter.

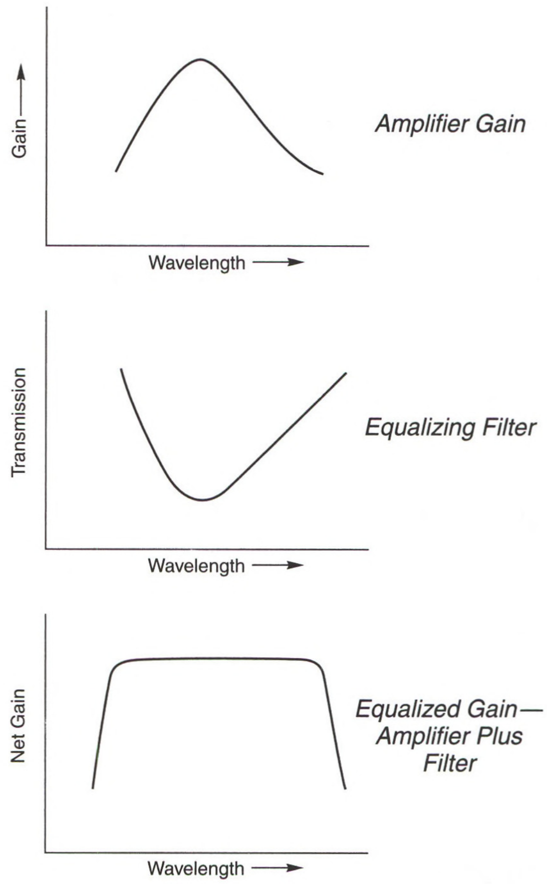


FIGURE 15.7
Equalizing filter balances uneven gain in a fiber amplifier.

resonate in the cavity. That is, an integral number *(N)* of wavelengths λ equals a round-trip distance in the cavity ($2L$):

$$2L = \frac{N\lambda}{n}$$

where n is the refractive index of the material between the mirrors, a quantity needed to account for the difference between the wavelength in empty space and the material.

The cavity transmits light at wavelengths that match this resonant condition, like an interference filter. In fact, the Fabry-Perot interferometer is just a simple version of an interference filter, with a single cavity instead of a stack of layers. Normally the Fabry-Perot cavity is short, so the spacing between wavelengths is large. Adjusting the cavity length changes the wavelength selected, tuning the filter. You adjust the length either by moving the mirrors or by tilting them so light follows a longer path between the mirrors.

Acoustic waves can create density waves in glass; changing the sound frequency adjusts the wavelength selected.

Another common approach is the acousto-optic filter, where acoustic waves travel through a transparent material such as glass. The atomic vibrations produced by the acoustic waves create regions of higher and lower density within the glass. The denser regions have higher refractive index, creating a multilayer structure in the glass. As in an interference filter or fiber grating, these regular high-index zones selectively scatter light of certain wavelengths selected by the spacing between them. Tuning the acoustic frequency changes the grating spacing, and hence the selected wavelength—making a tunable filter.

The big advantage of tunable filters is obviously their tunability. Their disadvantages are much greater cost and complexity than fixed wavelength filters.

WDM Technologies

Interference filters are one of several technologies available for WDM optics. Each of these technologies has distinct characteristics that fit into certain application requirements. Some are easy to implement for demultiplexing a few optical channels, while others easily handle large numbers of channels. Some work better for narrow optical channel separation than others. All achieve the basic goal of optical multiplexing and demultiplexing for some applications. Let's look at these diverse technologies one by one.

Several technologies are available for WDM optics.

Interference Filters for WDM

Using interference filters for WDM requires taking light out of the fiber and passing it through a set of filters that sorts the light out by wavelength. Typically a lens collimates or focuses the light emerging from the input fiber, which then passes through one or more filters. When the demultiplexing is finished, separate lenses collect the separated optical channels and focus them into individual output fibers.

Cascaded interference filters can pick off one wavelength at a time for demultiplexing.

A narrow-line interference filter typically transmits a single optical channel while reflecting other wavelengths. Several interference filters can be cascaded to pick off a series of six wavelengths, as shown in Figure 15.8. The first filter transmits channel λ_1 while

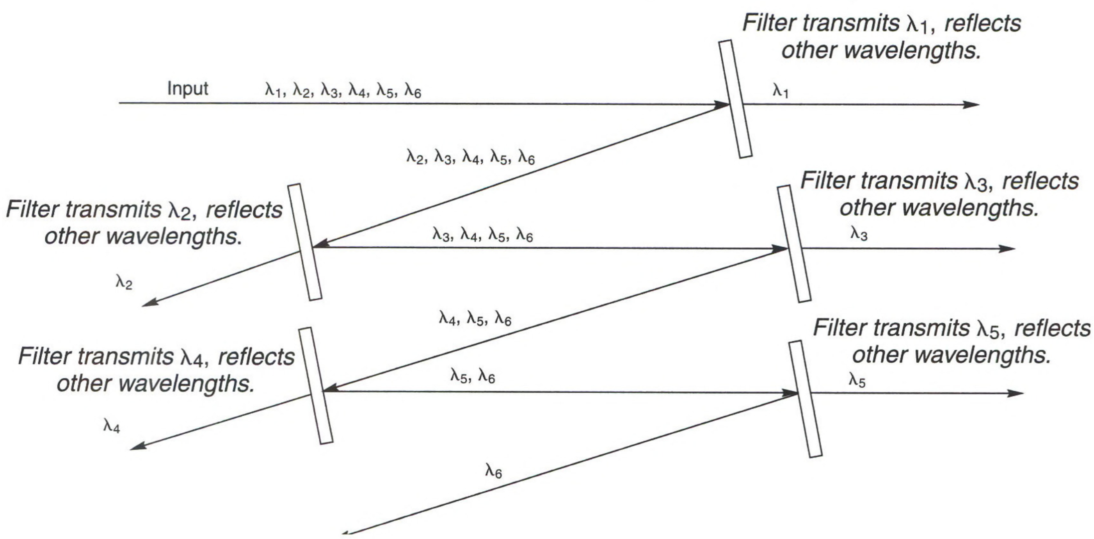


FIGURE 15.8

Interference filter WDM picks off one wavelength at a time.

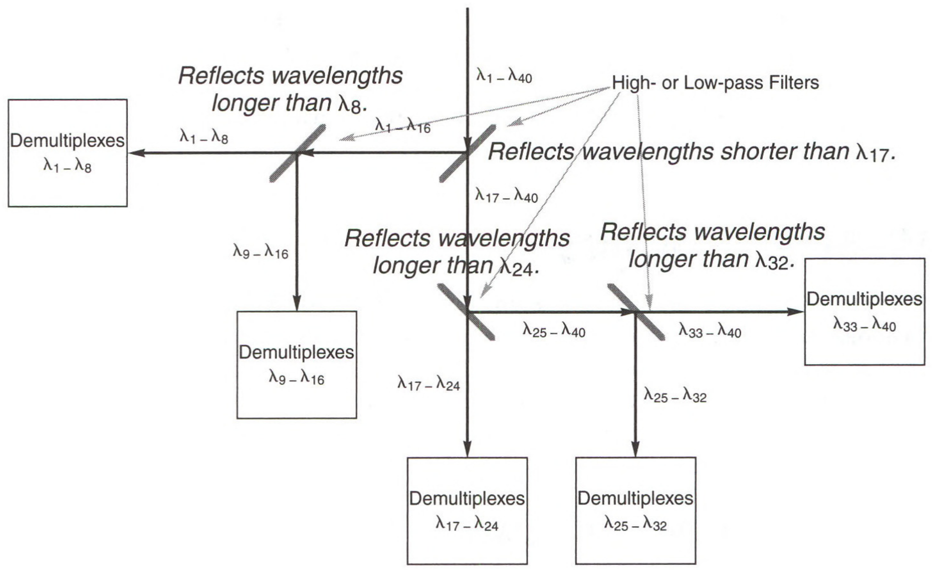


FIGURE 15.9
Demultiplexing 40 channels by separating blocks of channels.

reflecting all other channels. The remaining channels hit the second filter, which transmits channel λ_2 while reflecting the four remaining channels. In this arrangement you need $n - 1$ filters to isolate n optical channels.

The concept is simple and straightforward, but interference filters are not perfect. Although they reflect *virtually* all the incident light at other wavelengths, some is lost, and these losses add up after a series of reflections. Picking off one wavelength at a time works fine for 8 channels, but the losses could grow excessive if you have 16 or 32 channels.

Filters can divide optical channels into groups, then separate the groups into individual channels.

To prevent such losses, optical signals can be divided into groups of channels, which are then split up individually. Figure 15.9 shows such a system built from high- and low-pass filters plus 8-channel demultiplexers that pick off one channel at a time, as in Figure 15.8. In this scheme, incoming light first hits a high-pass filter, which reflects all light with wavelength less than λ_{17}. The shorter wavelengths are diverted to a low-pass filter, which reflects light with wavelengths longer than λ_8. Each of those sets of 8 channels is directed to an 8-channel demultiplexer. Wavelengths from λ_{17} to λ_{40} are routed to another low-pass filter, which reflects all light with wavelengths greater than λ_{24}. Channels λ_{17} to λ_{24} then go to an 8-channel demultiplexer, while the longer wavelengths are sent to another long-pass filter, which splits them into 8-channel groups for demultiplexing.

This approach does not reduce the *total* number of filters needed, but it does reduce the number of filters any optical channel is going to encounter before reaching a receiver. The upper limit for the configuration shown in Figure 15.9 is 10.

The arrangement shown in Figure 15.9 has another important advantage. It's modular, so you don't need to start with all 40 channels. You could start with channels λ_{17} to λ_{24}, then add the high- and low-pass filters to split off other wavelengths as you needed to add the extra channels. This is the way telephone companies like to work, adding capacity only as they need it. They save money in the short term, and retain the option for expanding capacity in the long term.

Interference filters are widely used for WDM, and it's worth reviewing their advantages. First, the underlying technology is well developed. Interference filters have been around for many years, although the extremely narrow-line filters used in DWDM systems were only developed very recently. Filters can be made very small—a few millimeters across—a good match for fiber-optic systems. They have good performance and can be assembled in modular units, so users can upgrade their systems several channels at a time, instead of jumping from 1 to 40 channels. On the down side, you need roughly as many filters as you have optical channels—adding to costs, complexity, and optical losses.

Filter WDMs can be upgraded modularly, but require about as many filters as the system has channels.

Remember also that interference filters do not always have to separate every single wavelength out of an optical signal. A single optical filter could transmit a single optical channel in an add-drop multiplexer, with the remaining channels reflected and collected for transmission through the rest of the system.

Fiber Bragg Gratings and Optical Circulators

Fiber Bragg gratings can be grouped together in ways similar to interference filters, but they have some significant functional differences. Generally they reflect a single selected wavelength and transmit the rest, as shown earlier in Figure 15.10. Recall that interference filters instead generally *transmit* the selected wavelength.

Fiber gratings reflect the selected wavelength and transmit other wavelengths.

This ability of fiber gratings to reflect a selected wavelength can be used to build an optical demultiplexer that resembles one based on interference filters. The important differences come from the facts that a fiber grating is a fiber, and that it reflects rather than transmits the wavelength it selected.

We'll start with the example shown in Figure 15.10, where the input signal includes eight wavelengths, 1546, 1548, 1550, 1552, 1554, 1556, 1558, and 1560 nm. The input signal enters the fiber grating through an optical circulator, described in Chapter 14, which acts like an optical traffic circle, transferring the signal from the input port to the grating. The grating transmits all the wavelengths except 1552 nm, which it reflects back to the optical circulator. The circulator is a directional device, so it transmits the light reflected from the fiber grating onto the drop port at bottom, where the light exits into another fiber that carries the signal to the 1552-nm receiver.

In a demultiplexer, the remaining seven input signals pass through the grating and become the input signal to a second fiber grating, which selectively reflects one of the remaining wavelengths. That wavelength is dropped to the appropriate receiver, and the remaining six channels continue, with one wavelength being picked off at a time. Like an

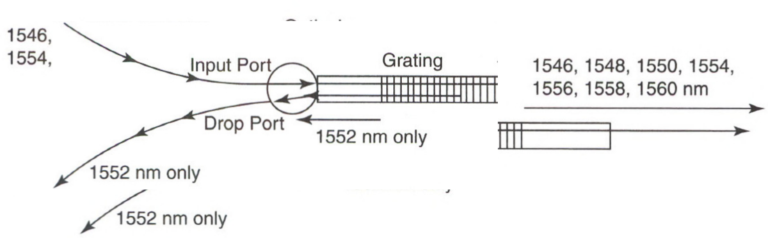


FIGURE 15.10
Fiber Bragg grating filter reflects the one wavelength it selects.

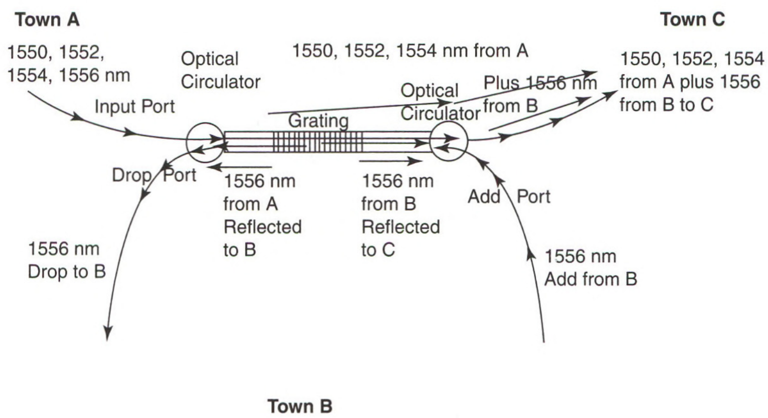


FIGURE 15.11 *A single fiber grating with optical circulators at both ends serves as an add-drop multiplexer.*

interference-filter demultiplexer, the fiber Bragg grating demultiplexer requires seven stages to separate eight channels.

Fiber gratings are natural choices for add-drop multiplexers.

Fiber gratings are a natural choice for use in add-drop multiplexing because the grating reflects the same wavelength when it enters from either end, so it can perform both add and drop functions, as shown in Figure 15.11. In this case, the fiber is carrying 1550, 1552, 1554, and 1556 nm. The 1556-nm signal is carrying information from town A to town B, while the others are carrying data from town A to town C. The system also is adding another 1556-nm signal from town B to town C. The grating first reflects the 1556-nm signal so it can be dropped at town B, transmitting 1550, 1552, and 1554 nm so they go to town C. The input signal at 1556 nm added at town B is coupled to the other end of the fiber grating through a second optical circulator. The grating reflects this signal back in the opposite direction, adding it to the original 1550, 1552, and 1554 nm signals on their way to town C through the circulator.

Fiber gratings have good wavelength selectivity, and can be used to demultiplex signals with channel spacing as fine as 25 GHz. However, a drawback for demultiplexing is that separation of the reflected wavelength requires optical circulators, which are complex and expensive. That leads to fiber gratings being picked for the narrow-band applications, where their selectivity is particularly important, while interference filters are used for applications, where narrow-band selectivity is not critical.

Fiber gratings can serve as optical filters as well as WDM filters.

The fiber-grating principle can be used to make other types of optical filters as well as WDM filters. Fiber gratings can be made with multiple grating sections along their length, each reflecting a different wavelength. As you learned in Chapter 7, one application is an optical delay line that compensates for chromatic dispersion in transmission fibers. Another is in an add-drop multiplexer that picks off two or more channels. Other designs allow fiber gratings to have complex attenuation properties spanning a range of wavelengths so they can serve as gain-equalization filters.

The fiber geometry of the fiber grating is at best a mixed blessing. As a fiber, it's easy to connect to transmission fibers. However, as a fiber it also reflects light back in the direction that the input signal arrived, so demultiplexers require an optical circulator to extract the selected wavelength. That's a problem because optical circulators are complex and expensive devices that can add considerably to system costs.

Fused-Fiber Couplers

The fused-fiber couplers described in Chapter 14 are inherently sensitive to wavelength. As in waveguide couplers, the amount of light transferred between the fused fibers depends on the length of the coupling region, as measured in wavelengths. Over some characteristic distance, the light is transferred completely from one output to the other. This distance is longer when measured in shorter wavelengths, because more of them fit into the same distance, opening a way to separate wavelengths.

Fused-fiber couplers can separate wavelengths by directing them out different ports.

The process works best for two wavelengths that are not closely spaced, so fused-fiber couplers are not used for separating optical channels in dense-WDM systems. However, it works fine for widely spaced wavelengths, like the pump and signal wavelengths in erbium-doped fiber amplifiers, as shown in Figure 15.12. Light initially enters the top of the two

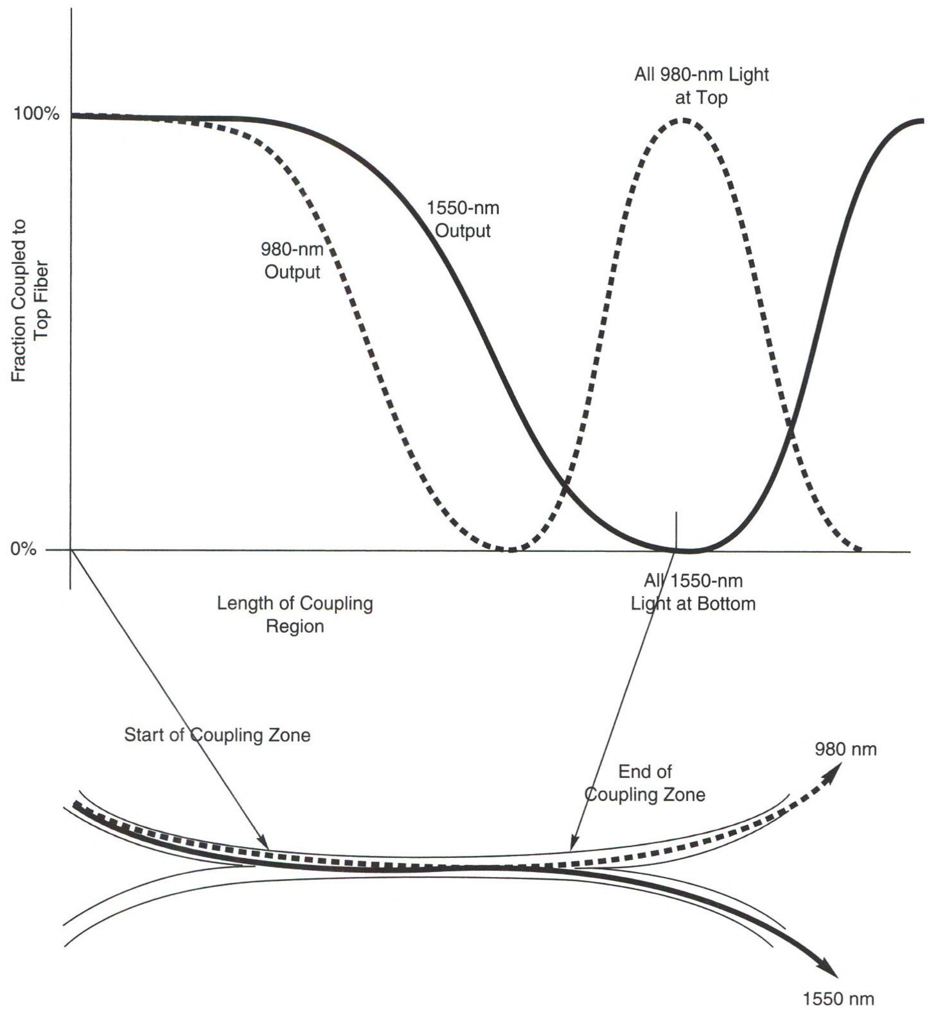


FIGURE 15.12
Fused-fiber coupler splits two wavelengths.

fused fibers. Gradually, the light shifts to the bottom fiber. If the fused region is long enough, all the light transfers into the lower fiber, and the process starts over again, this time shifting from the bottom to the top. The degree of shifting depends on how many wavelengths the light has travelled, so shorter wavelengths shift back and forth first, with longer wavelengths following. In Figure 15.12, the 980-nm light shifts from the top to the bottom fiber and back to the top at the end of the fused region, while the 1550-nm light has shifted only from the top to the bottom fiber. This process completely separates the two wavelengths.

Mach-Zehnder Interleavers

Mach-Zehnder interferometers interleave wavelengths, separating odd and even optical channels.

Fused-fiber couplers are essential components in another type of device for dense wavelength-division multiplexing called a *fused-fiber Mach-Zehnder interferometer*, or more simply an *interleaver.* Unlike other multiplexers and demultiplexers, these devices split groups of evenly spaced optical channels into sets of odd and even channels, by using the interference of light in a fiber structure. To see how they work, we'll start with a look at the concept of a Mach-Zehnder interferometer, named after the physicists who invented it.

Interferometers pass light waves along two different paths, causing interference between the waves. As you learned earlier, coherent light waves can add or subtract their amplitude, producing constructive or destructive interference. In a Mach-Zehnder interferometer, a device called a *beamsplitter* splits an input beam into two parts, which pass along different routes, then are combined in a second beamsplitter. Figure 15.13 shows how this can be done with fused-fiber couplers serving as the beamsplitters. Input enters through one fused-fiber coupler, where it is divided between two fibers that form the arms. Light in the two arms recombines in a second fused-fiber coupler.

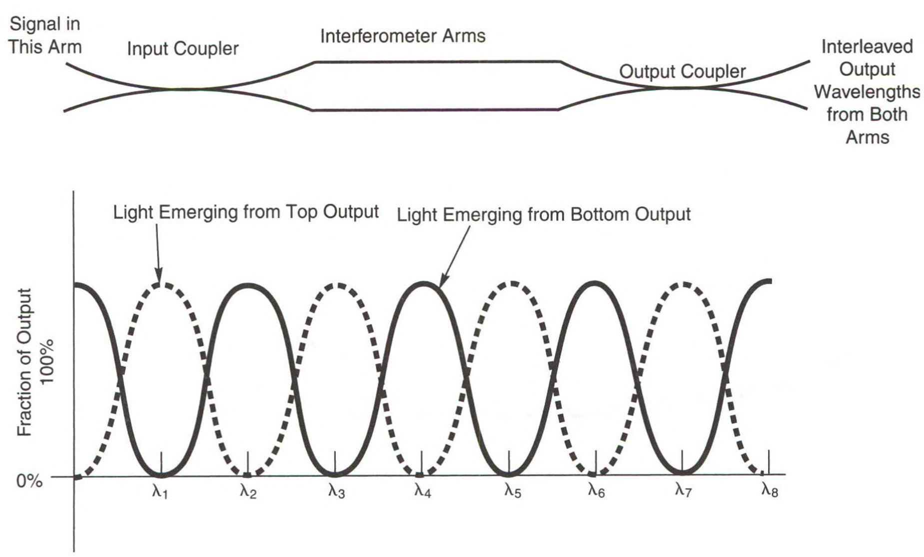


FIGURE 15.13
Fused-fiber coupler Mach-Zehnder interferometer interleaves wavelengths.

The relative phase of the light emerging from the interferometer arms determines its distribution between the two outputs of the output coupler. This phase depends on wavelength as well as the length of the arms. As the wavelength changes, the distribution of light between the two arms changes. In the case shown in Figure 15.13, at λ_1 all the light emerges from the top arm, but at λ_2 all the light emerges from the bottom arm. Every time the wavelength changes by that increment, the output light shifts between arms of the second fused-fiber coupler.

Incrementing frequency of an optical channel by $\Delta\nu$ shifts output between arms of the interleaver.

The increment in wavelength that shifts the output depends on the difference in effective length ΔL between the two interferometer arms. If we assume the two arms have the same refractive index n, this equals

$$\Delta L = \left(2n\left[\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right]\right)^{-1} = \frac{c}{2n\Delta\nu}$$

(The two arms could have different refractive indexes, which would complicate things.) Note that it's simpler to express the difference in terms of the change in *frequency*, $\Delta\nu$, rather than a change in wavelength. In fact, the increment in spacing of optical channels is uniform only if the spacing is measured in terms of a change in frequency $\Delta\nu$ rather than a change in wavelength. Thus the signals are at frequencies ν_1, $\nu_1 + \Delta\nu$, $\nu_1 + 2\Delta\nu$, $\nu_1 + 3\Delta\nu$, and so on. The difference between taking increments in terms of wavelength and in terms of frequency is small, but can be significant if you're designing systems. I label optical channels by their wavelength for convenience, but remember that actual DWDM channel spacing is uniform in frequency, *not* wavelength.

Interleavers essentially split odd and even optical channels. Thus in Figure 15.13, signals at λ_1, λ_3, λ_5, and λ_7 emerge entirely from the top output, while signals at λ_2, λ_4, λ_6, and λ_8 emerge entirely from the bottom output. This makes a fused-fiber Mach-Zehnder interferometer an effective wavelength interleaver that can demultiplex a set of uniformly spaced optical channels. The interleaver also can work backwards, shuffling odd and even optical channels together.

A single interleaver does not completely demultiplex the signals. In the example of Figure 15.13, you still have λ_1, λ_3, λ_5, and λ_7 in the top output, and λ_2, λ_4, λ_6, and λ_8 in the bottom output.

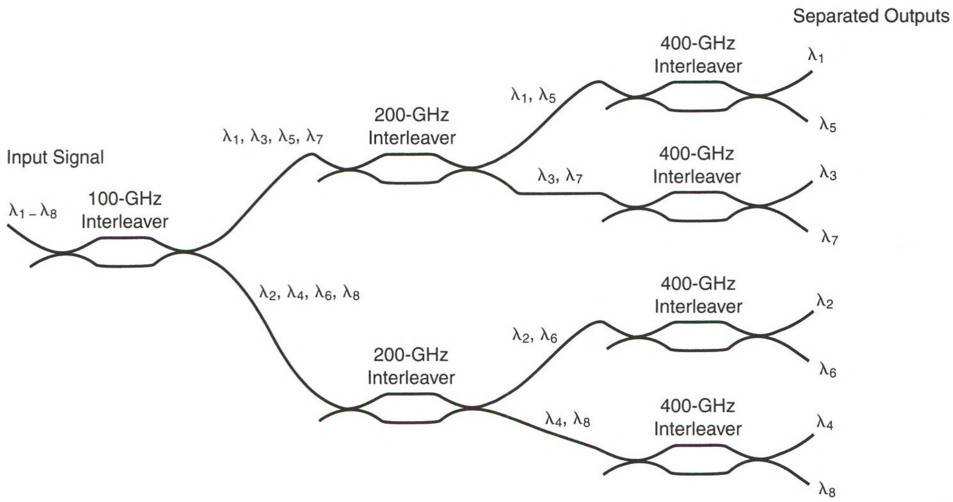
Interleavers separate or combine signals in several stages.

Those channels also must be separated, but you can do that by repeating the process, as shown in Figure 15.14. In this case, the first interleaver has the finest resolution—100 GHz (about 0.8 nm) in the example. The next interleaver needs to split the remaining channels, so it splits channels twice as far apart—200 GHz. The final interleaving demultiplexer must split the two channels left in each output fiber, so it needs 400-GHz spacing (about 3.2 nm).

Note that Mach-Zehnder interferometers can be built with planar-waveguide technology as well as with fused-fiber couplers. So far, the main application of planar waveguides has been in the multi-arm arrayed waveguide devices described below, but two-arm Mach-Zehnder interleavers also can be made using planar waveguides.

As you can see, interleaving is a different process than picking one signal off at a time with an interference filter or fiber Bragg grating. Demultiplexing eight channels requires the same number of components—seven—whether you use interference filters or interleavers. However, with interleavers all signals pass through three components; with the

FIGURE 15.14
Interleavers demultiplex optical channels in stages.



interference filter demultiplexer shown in Figure 15.8, the final two channels have to pass through all seven filters, so they experience more loss than the other channels.

The differences between interleavers and other demultiplexers are important to remember. As you will see later, these differences are vital in designing hybrid WDM systems that take advantage of the strengths of two (or more) different approaches.

Bulk Diffraction Gratings

Diffraction gratings separate wavelengths by spreading out a spectrum.

I mentioned earlier that a diffraction grating—a series of parallel grooves or lines—diffracts light in a way that spreads out a spectrum. Interference between light waves scatters different wavelengths from the grating at different angles. The gory details of the optical physics aren't important here; what matters is that the wavelengths spread out, like a rainbow. You can see the same rainbow effect in a CD if you tilt it back and forth while looking at light reflected from it. The pits that store data on the CD are arranged in grooves that wind in a tight spiral around the disk, forming sets of parallel spots that act like a diffraction grating.

You can use the same effect to separate wavelengths, with suitable optics to focus the input light, collect the reflected light, and focus it into the output fibers.

Figure 15.15 shows a grating demultiplexer. This device uses a gradient-index (GRIN) rod lens in which the refractive index varies through a block of solid glass, producing the same focusing effect as a standard lens. (A GRIN lens is easier to align than a standard lens for this application.)

Input on three optical channels, λ_1, λ_2, and λ_3, enters through the bottom fiber. The GRIN rod focuses the input light onto a diffraction grating at the back end of the rod, which is set at an angle to reflect the light at the right angle. The grating diffracts each wavelength at a different angle, and the GRIN rod focuses each wavelength onto an output fiber. When everything is properly aligned (which, of course, is a big part of the job),

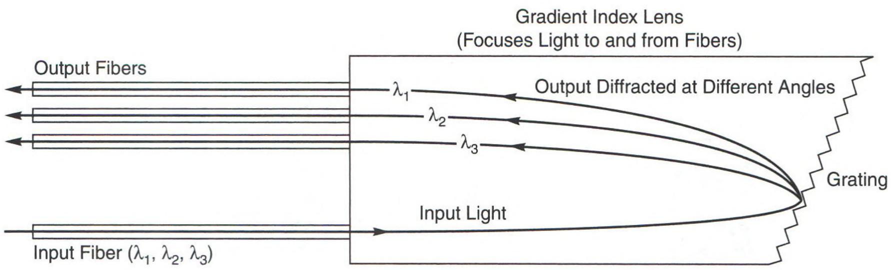


FIGURE 15.15
A grating coupler with GRIN rod separates three wavelengths.

λ_1 emerges from the top output fiber, λ_2 emerges from the middle output fiber, and λ_3 emerges from the lowest output fiber.

Such simple bulk diffraction grating demultiplexers work well for separating a few wavelengths that are widely spaced, but they don't give high channel isolation between closely spaced wavelengths. However, the way that diffraction gratings spread out a continuous spectrum of wavelengths is an advantage for measurement instruments. If you want to measure the distribution of power as a function of wavelength, you usually want resolution finer than you need to look at a single channel. Scanning a continuous spectrum gives better resolution, and a diffraction grating makes this spectrum available. Thus measurement instruments are likely to use diffraction gratings to spread out the spectra that they measure. (The same is true for optical performance monitors, which measure the distribution of optical power across the spectrum in communication systems to check that all channels are operating properly.)

Special diffraction gratings called *echelle gratings* offer higher resolution than ordinary gratings, which makes them potentially attractive for use in DWDM. That technology and other grating multiplexers are still in development.

Arrayed Waveguide Gratings

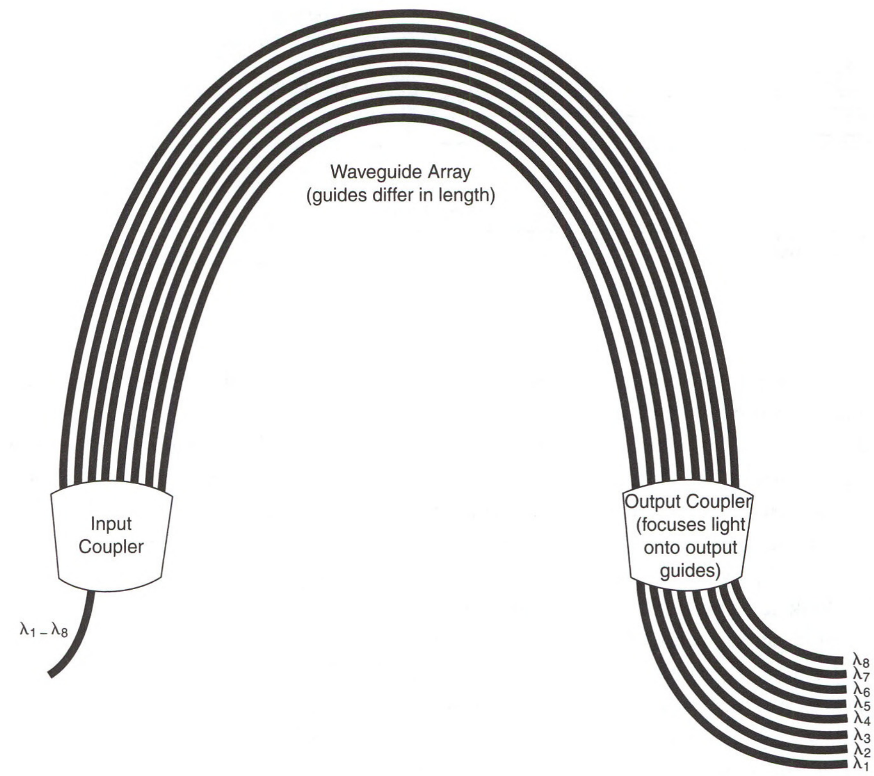
Another way to demultiplex WDM signals is to pass them through an array of planar waveguides, as shown in Figure 15.16. Like a diffraction grating, an *arrayed waveguide grating (AWG)* diffracts light at angles that depend on the wavelength, so the technology also can be used for other applications including dynamic gain equalization, reconfigurable optical add/drop multiplexers, and wavelength-selectable lasers. You can think of an arrayed waveguide grating as a diffraction grating built using planar waveguide technology.

An AWG is a planar waveguide version of a diffraction grating.

The central element is an array of narrow curved waveguides running beside each other between a pair of mixing regions or coupling zones. Input signals enter the first mixing region (at left in Figure 15.16), where they are coupled into the curved waveguides running to the second mixing region. The adjacent waveguides differ in length by an increment ΔL, which is much larger than the wavelength λ. As a result of this difference, light passing in adjacent waveguides between the two mixing regions has a phase shift of $n\Delta L/\lambda$, where n is the refractive index of the waveguide. This phase shift acts like a diffraction grating to disperse light across a range of angles in the second mixing region.

The second mixing region acts like a lens to focus the diffracted light onto a series of output ports. Interference effects combine with the refraction and diffraction to disperse a

FIGURE 15.16
Array waveguide demultiplexer.



spectrum of light across the output ports, so each port collects a limited range of wavelengths. In versions built for demultiplexing, each port collects wavelengths corresponding to one standard WDM optical channel. The number of output ports is the number of channels separated, with the free spectral range of the device equaling the channel spacing times the number of channels. The number of waveguides running between the two mixing regions is larger than the number of channels; for example, a 64-channel waveguide AWG has an array of 232 waveguides linking the mixing regions.

Arrayed waveguides can be made from silica, plastic, silicon, or III-V semiconductors such as indium phosphide. The devices are monolithic and can be integrated with other components such as optical switches. Like integrated electronic circuits, the master is expensive, but replication is relatively cheap. From a functional standpoint, an arrayed waveguide is a monolithic device that can separate many optical channels simultaneously. Filters require complex assemblies of many discrete components to do the same job.

AWG demultiplexers are best for high channel counts.

Arrayed waveguides are used mainly in demultiplexing optical systems with high channel counts, where the cost per channel is much lower than with other WDM technologies. Laboratory versions have been made containing hundreds of channels spaced as little as 10 GHz apart, but typical commercial versions have 32 or 40 channels spaced at 50 or 100 GHz. AWGs can be used in reverse for multiplexing.

Standard arrayed waveguides have peak transmission in the center of the band, which declines gradually to the sides, as in Figure 15.3. Often some other optics are added to flatten the peak transmission and make the sides drop faster to prevent crosstalk. For example, an interleaver can split signals between a pair of AWGs so one receives the odd channels and the other the even channels.

One inherent limitation of arrayed waveguides is a high insertion loss arising from mismatches of transmission modes in the waveguides and in the mixing region. AWGs also are sensitive to temperature, and some materials—notably III-V semiconductors—are sensitive to polarization.

Array waveguide technology lends itself to other applications that require wavelength selectivity. For example, a pair of AWGs can be integrated with other devices to separate the wavelengths in an input signal, process the separated wavelengths, then recombine them in a multiplexer. This approach can be used to make a reconfigurable optical add/drop multiplexer, with switches placed in the path individual optical channels take between the demultiplexer and multiplexer. Variable filters could be put in the same position to make a dynamic gain equalization filter, which changes transmission to compensate for fluctuations in amplifier gain.

Building Multiplexers and Demultiplexers

So far you've learned the general principles of WDM optics. A few other considerations go into building actual multiplexers and demultiplexers.

Multiple technologies can be integrated in a single multiplexer or demultiplexer.

You should realize that these technologies are building blocks. Actual systems may integrate two or more WDM technologies into a single multiplexer or demultiplexer. These hybrid WDMs can take advantage of the best features of the different technologies. For example, you could use a Mach-Zehnder interleaver as the first stage, to break up an 16-channel signal with 100-GHz spacing into two 8-channel signals with 200 GHz spacing. Then interference filters with 200-GHz resolution could break up the 8-channel signals. This could cut costs significantly because 200-GHz filters are much less expensive than 100-GHz filters. Similarly, two interleaving stages—one at 50 GHz, the other at 100 GHz—could break down a 32-channel signal with 50 GHz spacing to four separate 8-channel signals with 200-GHz channel spacing.

In talking about general principles, it's easiest to assume that channels are uniformly spaced, and that every slot is filled. This does not happen in general. The spacing of channel slots generally is uniform, but the channels may be grouped into blocks, and not all of the slots may be filled. For example, one or two channel slots may be left between 8-channel blocks in a system like the one shown in Figure 15.9, if the band-pass filters do not have sharp enough cutoffs. In practice, a gap of about 5 nm normally is left between the erbium fiber amplifier C-band at 1530 to 1565 nm and the L-band at 1570 to 1620 nm.

The ability to add more channels at reasonable cost is a major practical concern. Telecommunications carriers want room to increase their transmission capacity, but they don't want to pay for large amounts of equipment they can't use immediately. For example, they might like to build the 40-channel system shown in Figure 15.9 in increments of eight channels at a time. This has to be traded off against the possibly lower overall cost of installing a larger system all at once.

Finally, remember that not every possible channel slot has to be used. Many market analysts during the telecommunications bubble wrongly assumed that carriers were buying lots of WDM systems and filling all of the wavelength slots. That led to wildly inflated estimates of the growth of network capacity.

A prudent carrier may plan to use 16 or 32 channels on a single fiber eventually, but at first they are more likely to start with a couple of channels. They may install only the optics they need for two channels, then plan to add more modules later. Or if the price is right, they may go for an 8-channel optics package and fill the remaining slots later. Like spare fibers in a cable, the extra optical channels don't cost much until the transmitters, receivers, and optical amplifiers are installed. Network planners like to leave room for future growth. Like installing new electrical wiring in your house, you plan not just for the equipment you already own, but for what you expect to add in coming years.

What Have You Learned?

1. WDM optics combine optical channels at the input end of a system and separate them after transmission through a fiber. Multiplexers combine channels; demultiplexers separate them.
2. An add-drop multiplexer goes in the middle of a system. It can both drop existing channels at an intermediate point and add new channels to a fiber carrying WDM signals. The added signal can replace the dropped channel.
3. Channel density depends on spacing between channels. Standard spacings for dense-WDM spacings are 200, 100, and 50 GHz. Coarse-WDM channel spacing is 20 nm.
4. Wavelength routers direct different wavelengths to different points.
5. Separating pump wavelengths from the outputs of fiber amplifiers also requires wavelength-division multiplexing.
6. WDM filters transmit selected wavelengths and reflect others.
7. An interference filter uses multiple thin layers to selectively transmit a narrow range of wavelengths; others are reflected. Interference filters can select a very narrow range of wavelengths.
8. Cutoff filters make a sharp transmission between transmitting and reflecting at a certain wavelength.
9. Equalizing filters compensate for the unequal gain of optical amplifiers across their operating ranges.
10. Most filters have fixed wavelength response, but some can be tuned to transmit different wavelengths. They include acousto-optic filters and Fabry-Perot interferometers.
11. Interference filters can select closely spaced optical channels. A cascaded series of interference filters can pick off one wavelength at a time to demultiplex optical channels. Each filter transmits one channel and reflects the rest.
12. Interference filters can select groups of optical channels as well as individual channels.

13. Fiber Bragg gratings reflect the selected wavelength and transmit other wavelengths. They must be used together with optical circulators for demultiplexing, but have high resolution in selecting optical channels.
14. Fused-fiber couplers can separate wavelengths by directing them out different ports, but their resolution is limited.
15. Mach-Zehnder interferometers interleave wavelengths, directing alternating channels out of each of two inputs. They are sometimes called interleavers, and can separate closely spaced optical channels. Interleavers separate channels in a series of stages.
16. Bulk diffraction gratings separate wavelengths by spreading out a spectrum. They are often used for measurement instruments.
17. Arrayed waveguides are planar waveguide devices that disperse light by its wavelength, like diffraction gratings. The arrays are monolithic, and can separate closely spaced optical channels. They are most economical for 32 or 40 optical channels.
18. WDM systems may combine multiple technologies for demultiplexing.

What's Next?

Chapter 16 will cover optical switches, optical modulators, and other active devices used in optical networks.

Further Reading

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

Kenneth O. Hill, "Fiber Bragg Gratings," Chapter 9 in Michael Bass, ed., *Handbook of Optics Vol. IV: Fiber Optics & Nonlinear Optics* (McGraw-Hill, 2001)

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

Questions to Think About

1. An erbium-doped fiber amplifier can transmit signals at wavelengths between 1530 and 1565 nm. How many optical channels can you fit in this range with 200 GHz spacing? How many channels with 100 GHz spacing?
2. A transatlantic fiber-optic cable contains 100 optical amplifiers. It needs equalizing filters to balance the gain of the erbium-fiber amplifiers across their

operating ranges. If the receivers used on the system have a dynamic range of 20 dB, how closely do the equalizing filters have to balance gain? Assume all filters and amplifiers are identical.

3. A typical interference filter for demultiplexing 100-GHz channels has 0.5-dB loss on the reflected channels and 2.0-dB loss on the transmitted channels. How much loss does the signal suffer on the first channel picked off (λ_1) in Figure 15.8? What is the loss for the last channel of eight channels picked off (λ_8) in a similar arrangement? What channel in an 8-channel system suffers the highest total loss?
4. A typical fiber Bragg grating has 99.9% reflection (0.0043-dB loss) and 0.2-dB loss for transmitted wavelengths. Assume loss of 1 dB in the optical circulator. What is the loss for the first channel of eight channels picked off in a cascaded series of fiber Bragg gratings? What are losses for the seventh and eighth channels?
5. What should the difference in path lengths be in a Mach-Zehnder interferometer designed to interleave optical channels separated by 50 GHz? By 200 GHz? Assume the refractive index of the material is 1.5 and is uniform for both arms.
6. You want to separate 16 optical channels that are uniformly spaced 50 GHz apart with optical interleavers. How many interleavers do you need? How many interleavers does each optical channel pass through?
7. A 40-channel arrayed waveguide demultiplexer has average loss of 8 dB for each channel processed. How does this compare to the highest loss of the 40-channel interference-filter demultiplexer shown in Figure 15.9? You can use the results from Question 3 to give you the loss for the 8-channel demultiplexing boxes. What's the minimum loss?

Chapter Quiz

1. What is the broadest channel spacing that is considered "dense" WDM?
   a. 400 GHz
   b. 200 GHz
   c. 100 GHz
   d. 50 GHz
   e. 0.8 nm
2. What does an add-drop multiplexer do?
   a. converts all optical signals in a fiber to electronic form
   b. amplifies optical signals after attenuation has reduced signal strength below 1 μW per optical channel
   c. adds and drops optical channels at intermediate locations without interfering with other signals on the fiber

d. adds and drops optical channels at an intermediate point while regenerating other channels on the fiber

e. switches signals between different wavelengths at an intermediate point in the system

3. What selects the wavelengths transmitted by an interference filter?

a. the thickness and composition of layers deposited on glass

b. the composition of the glass plate on which it is deposited

c. coloring dyes added to the layers in the interference filter

d. parallel ridges formed in the uppermost layer

e. only the refractive index of the surface layer

4. You want to reflect light at wavelengths longer than 1567 nm and transmit light at shorter wavelengths. What type of filter do you want?

a. color filter

b. cutoff filter

c. band-pass filter

d. line filter

e. attenuation filter

5. What type of filter is tunable in wavelength?

a. interference filter

b. cutoff filter

c. band-pass filter

d. Fabry-Perot interferometer

e. line filter

6. An acousto-optic filter is

a. a type of cutoff filter.

b. a tunable filter.

c. an interference filter.

d. a color filter.

e. impossible to build.

7. Interference filters

a. reflect the selected wavelength and absorb other wavelengths.

b. reflect the selected wavelength and transmit other light.

c. transmit the selected wavelength and reflect other wavelengths.

d. transmit the selected wavelength and absorb other light.

8. What type of WDM system requires an optical circulator?

a. interference filters

b. fiber Bragg gratings

c. Mach-Zehnder interferometers or interleavers
d. bulk diffraction gratings
e. tunable optical filters

9. Fiber Bragg gratings

a. reflect the selected wavelengths and absorb other wavelengths.
b. reflect the selected wavelength and transmit other light.
c. transmit the selected wavelength and reflect other wavelengths.
d. transmit the selected wavelength and absorb other light.

10. What type of technology is used in an interleaver?

a. cutoff filter
b. interference filter
c. fiber Bragg grating
d. Mach-Zehnder interferometer
e. Fabry-Perot interferometer

11. How many interference filters do you need to make an 8-channel demultiplexer that picks off one channel at a time?

a. 4
b. 6
c. 7
d. 8
e. 9

12. How many fiber gratings do you need to make an 8-channel demultiplexer that picks off one channel at a time?

a. 4
b. 6
c. 7
d. 8
e. 9