Optical Communication Networks

EE654

Lecture-2

Spring 2016

2. Components

The components used in modern optical networks include couplers, lasers, photodetectors, optical amplifiers, optical switches, and filters and multiplexers. Couplers are simple components used to combine or split optical signals. After describing couplers, we will cover filters and multiplexers, which are used to multiplex and demultiplex signals at different wavelengths in WDM systems. We then describe various types of optical amplifiers, which are key elements used to overcome fiber and other component losses and, in many cases, can be used to amplify signals at multiple wavelengths. Understanding filters and optical amplifiers is essential to understanding the operation of lasers, which comes next. Semiconductor lasers are the main transmitters used in optical communication systems. Then we discuss photodetectors, which convert the optical signal back into the electrical domain. This is followed by optical switches, which play an important role as optical networks become more agile. Finally, we cover wavelength converters, which are used to convert signals from one wavelength to another, at the edges of the optical network, as well as inside the network.

2.1 Couplers

A *directional coupler* is used to combine and split signals in an optical network. A 2×2 coupler consists of two input ports and two output ports, as is shown in Figure 3.1. The most commonly used couplers are made by fusing two fibers together in the middle—these are called fused fiber couplers. Couplers can also be fabricated using waveguides in integrated optics. A 2×2 coupler, shown in Figure 3.1, takes a fraction α of the power from input 1 and places it on output 1 and the remaining fraction $1 - \alpha$ on output 2. Similarly, a fraction $1 - \alpha$ of the power from input 2 is distributed to output 1 and the remaining power to output 2. We call α the coupling ratio.

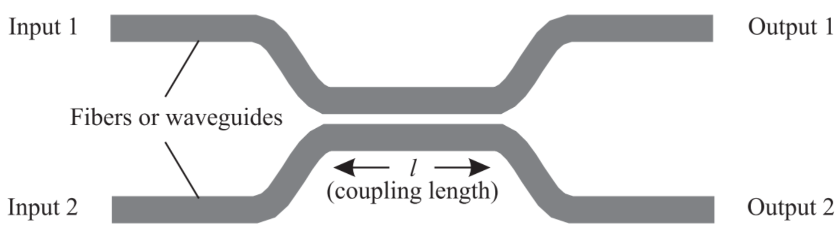

Figure 3.1 A directional coupler. The coupler is typically built by fusing two fibers together. It can also be built using waveguides in integrated optics.

The coupler can be designed to be either wavelength selective or wavelength independent (sometimes called wavelength flat) over a usefully wide range. In a wavelength-independent device, α is independent of the wavelength; in a wavelength-selective device, α depends on the wavelength.

A coupler is a versatile device and has many applications in an optical network. The simplest application is to combine or split signals in the network. For example, a coupler can be used to distribute an input signal equally among two output ports if the coupling length, l in Figure 3.1, is adjusted such that half the power from each input appears at each output. Such a coupler is called a 3 dB coupler. An $n \times n$ star coupler is a natural generalization of the 3 dB 2×2 coupler. It is an n-input, n-output device with the property that the power from each input is divided equally among all the outputs. An $n \times n$ star coupler can be constructed by suitably interconnecting a number of 3 dB couplers, as shown in Figure 3.2. A star coupler is useful when multiple signals need to be combined and broadcast to many outputs. However, other constructions of an $n \times n$ coupler in integrated optics are also possible (see, for example, [Dra89]).

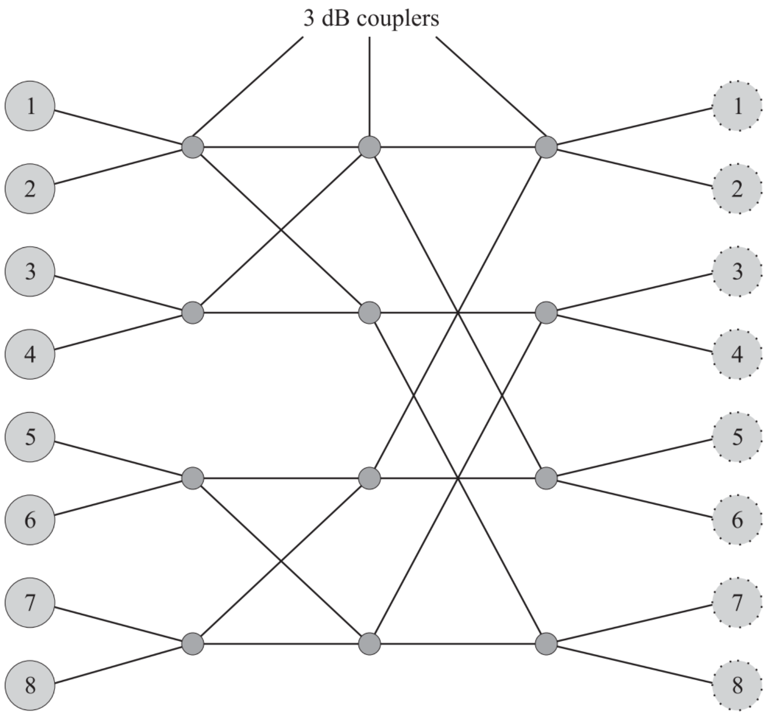

Figure 3.2 A star coupler with eight inputs and eight outputs made by combining 3 dB couplers. The power from each input is split equally among all the outputs.

Couplers are also used to tap off a small portion of the power from a light stream for monitoring purposes or other reasons. Such couplers are also called taps and are designed with values of α close to 1, typically 0.90–0.95.

So far, we have looked at wavelength-independent couplers. A coupler can be made wavelength selective, meaning that its coupling coefficient will then depend on the wavelength of the signal. Such couplers are widely used to combine signals at 1310 nm and 1550 nm into a single fiber without loss. In this case, the 1310 nm signal on input 1 is passed through to output 1, whereas the 1550 nm signal on input 2 is passed through also to output 1. The same coupler can also be used to separate the two signals coming in on a common fiber. Wavelength-dependent couplers are also used to combine 980 nm or 1480 nm pump signals along with a 1550 nm signal into an erbium-doped fiber amplifier; see Figures 3.34 and 3.37.

In addition to the coupling ratio α, we need to look at a few other parameters while selecting couplers for network applications. The *excess loss* is the loss of the device above the fundamental loss introduced by the coupling ratio α. For example, a 3 dB coupler has a nominal loss of 3 dB but may introduce additional losses of, say, 0.2 dB. The other parameter is the variation of the coupling ratio α compared to its nominal value, due to tolerances in manufacturing, as well as wavelength dependence. In addition, we also need to maintain low *polarization-dependent loss* (PDL) for most applications.

2.1.1 Principles of Operation

When two waveguides are placed in proximity to each other, as shown in Figure 3.1, light "couples" from one waveguide to the other. This is because the propagation modes of the combined waveguide are quite different from the propagation modes of a single waveguide due to the presence of the other waveguide. When the two waveguides are identical, which is the only case we consider in this book, light launched into one waveguide couples to the other waveguide completely and then back to the first waveguide in a periodic manner. A quantitative analysis of this coupling phenomenon must be made using *coupled mode theory* [Yar97] and is beyond the scope of this book. The net result of this analysis is that the electric fields, E_{o1} and E_{o2}, at the outputs of a directional coupler may be expressed in terms of the electric fields at the inputs E_{i1} and E_{i2}, as follows:

$$\begin{pmatrix} E_{o1}(f) \\ E_{o2}(f) \end{pmatrix} = e^{-i\beta l} \begin{pmatrix} \cos(\kappa l) & i\sin(\kappa l) \\ i\sin(\kappa l) & \cos(\kappa l) \end{pmatrix} \begin{pmatrix} E_{i1}(f) \\ E_{i2}(f) \end{pmatrix}. \tag{3.1}$$

Here, l denotes the coupling length (see Figure 3.1), and β is the propagation constant in each of the two waveguides of the directional coupler. The quantity κ is called the *coupling coefficient* and is a function of the width of the waveguides, the refractive indices of the waveguiding region (core) and the substrate, and the proximity of the two waveguides. Equation (3.1) will prove useful in deriving the transfer functions of more complex devices built using directional couplers (see Problem 3.1).

Although the directional coupler is a two-input, two-output device, it is often used with only one active input, say, input 1. In this case, the power transfer function of the directional coupler is

$$\begin{pmatrix} T_{11}(f) \\ T_{12}(f) \end{pmatrix} = \begin{pmatrix} \cos^2(\kappa l) \\ \sin^2(\kappa l) \end{pmatrix}. \tag{3.2}$$

Here, $T_{ij}(f)$ represents the power transfer function from input i to output j and is defined by $T_{ij}(f) = |E_{oj}|^2/|E_{ii}|^2$. Equation (3.2) can be derived from (3.1) by setting $E_{i2} = 0$.

Note from (3.2) that for a 3 dB coupler the coupling length must be chosen to satisfy $\kappa l = (2k+1)\pi/4$, where k is a nonnegative integer.

2.1.2 Conservation of Energy

The general form of (3.1) can be derived merely by assuming that the directional coupler is lossless. Assume that the input and output electric fields are related by a general equation of the form

$$\begin{pmatrix} E_{o1} \\ E_{o2} \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{pmatrix} \begin{pmatrix} E_{i1} \\ E_{i2} \end{pmatrix}. \tag{3.3}$$

The matrix

$$\mathbf{S} = \begin{pmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{pmatrix}$$

is the transfer function of the device relating the input and output electric fields and is called the *scattering matrix*. We use complex representations for the input and output electric fields, and thus the s_{ij} are also complex. It is understood that we must consider the real part of these complex fields in applications. This complex representation for the s_{ij} allows us to conveniently represent any induced phase shifts.

For convenience, we denote $\mathbf{E}_o = (E_{o1}, E_{o2})^T$ and $\mathbf{E}_i = (E_{i1}, E_{i2})^T$, where the superscript T denotes the transpose of the vector/matrix. In this notation, (3.3) can be written compactly as $\mathbf{E}_o = \mathbf{S}\mathbf{E}_i$.

The sum of the powers of the input fields is proportional to $\mathbf{E}_i^T\mathbf{E}_i^* = |E_{i1}|^2 + |E_{i2}|^2$. Here, * represents the complex conjugate. Similarly, the sum of the powers of the output fields is proportional to $\mathbf{E}_o^T\mathbf{E}_o^* = |E_{o1}|^2 + |E_{o2}|^2$. If the directional coupler is lossless, the power in the output fields must equal the power in the input fields so that

$$\begin{aligned} \mathbf{E}_o^T\mathbf{E}_o &= (\mathbf{S}\mathbf{E}_i)^T(\mathbf{S}\mathbf{E}_i)^* \\ &= \mathbf{E}_i^T(\mathbf{S}^T\mathbf{S}^*)\mathbf{E}_i^* \\ &= \mathbf{E}_i^T\mathbf{E}_i^*. \end{aligned}$$

Since this relationship must hold for arbitrary $\mathbf{E}_i$, we must have

$$\mathbf{S}^T\mathbf{S}^* = \mathbf{I}, \tag{3.4}$$

where $\mathbf{I}$ is the identity matrix. Note that this relation follows merely from conservation of energy and can be readily generalized to a device with an arbitrary number of inputs and outputs.

2.2 Isolators and Circulators

Couplers and most other passive optical devices are *reciprocal* devices in that the devices work exactly the same way if their inputs and outputs are reversed. However, in many systems there is a need for a passive *nonreciprocal* device. An *isolator* is an example of such a device. Its main function is to allow transmission in one direction through it but block all transmission in the other direction. Isolators are used in systems at the output of optical amplifiers and lasers primarily to prevent reflections from entering these devices, which would otherwise degrade their performance. The

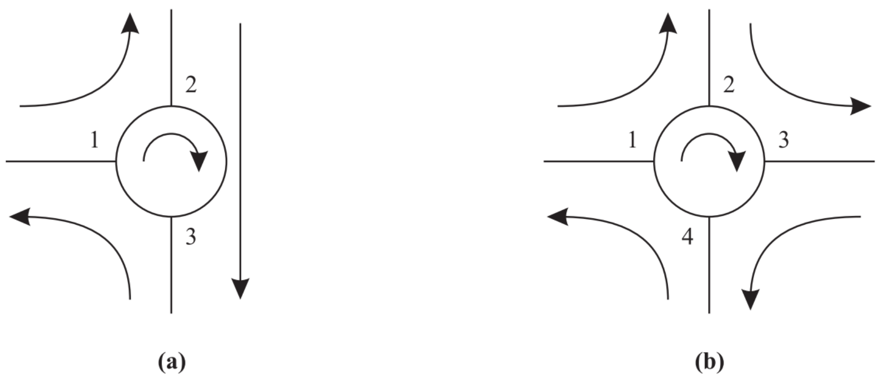

Figure 3.3 Functional representation of circulators: (a) three-port and (b) four-port. The arrows represent the direction of signal flow.

two key parameters of an isolator are its *insertion loss*, which is the loss in the forward direction and which should be as small as possible, and its *isolation*, which is the loss in the reverse direction and which should be as large as possible. The typical insertion loss is around 1 dB, and the isolation is around 40–50 dB.

A *circulator* is similar to an isolator, except that it has multiple ports, typically three or four, as shown in Figure 3.3. In a three-port circulator, an input signal on port 1 is sent out on port 2, an input signal on port 2 is sent out on port 3, and an input signal on port 3 is sent out on port 1. Circulators are useful to construct optical add/drop elements, as we will see in Section 3.3.4. Circulators operate on the same principles as isolators; therefore we only describe the details of how isolators work next.

2.2.1 Principles of Operation

The principle of operation of an isolator is shown in Figure 3.4. Assume that the input light signal has the vertical SOP shown in the figure. It is passed through a *polarizer*, which passes only light energy in the vertical SOP and blocks light energy in the horizontal SOP. Such polarizers can be realized using crystals, called *dichroics,*

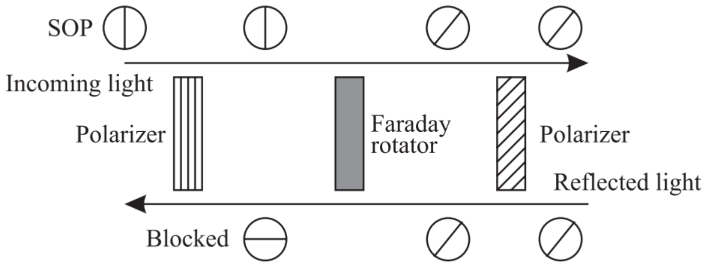

Figure 3.4 Principle of operation of an isolator that works only for a particular state of polarization of the input signal.

which have the property of selectively absorbing light with one SOP. The polarizer is followed by a *Faraday rotator*. A Faraday rotator is a nonreciprocal device, made of a crystal that rotates the SOP, say, clockwise, by 45°, regardless of the direction of propagation. The Faraday rotator is followed by another polarizer that passes only SOPs with this 45° orientation. Thus the light signal from left to right is passed through the device without any loss. On the other hand, light entering the device from the right due to a reflection, with the same 45° SOP orientation, is rotated another 45° by the Faraday rotator, and thus blocked by the first polarizer.

Note that the preceding explanation assumes a particular SOP for the input light signal. In practice we cannot control the SOP of the input, and so the isolator must work regardless of the input SOP. This requires a more complicated design, and many different designs exist. One such design for a miniature polarization-independent isolator is shown in Figure 3.5. The input signal with an arbitrary SOP is first sent through a *spatial walk-off polarizer* (SWP). The SWP splits the signal into its two orthogonally polarized components. Such an SWP can be realized using *birefringent* crystals whose refractive index is different for the two components. When light with an arbitrary SOP is incident on such a crystal, the two orthogonally polarized components are refracted at different angles. Each component goes through a Faraday rotator, which rotates the SOPs by 45°. The Faraday rotator is followed by a *half-wave plate*. The half-wave plate (a reciprocal device) rotates the SOPs by 45° in the clockwise direction for signals propagating from left to right, and by 45° in the counterclockwise direction for signals propagating from right to left. Therefore, the combination of the Faraday rotator and the half-wave plate converts the horizontal polarization into a vertical polarization and vice versa, and the two signals are combined by another SWP at the output. For reflected signals in the reverse direction, the half-wave plate and Faraday rotator cancel each other's effects, and the SOPs remain unchanged as they pass through these two devices and are thus not recombined by the SWP at the input.

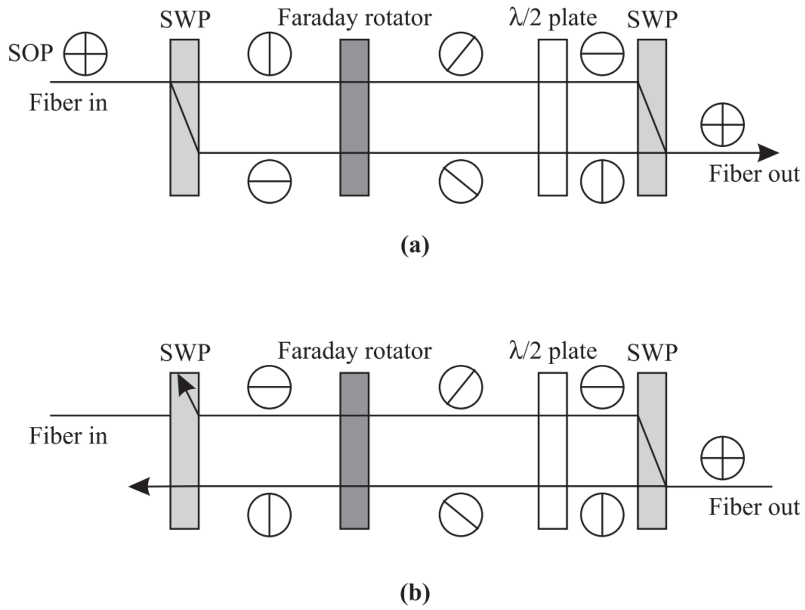

Figure 3.5 A polarization-independent isolator. The isolator is constructed along the same lines as a polarization-dependent isolator but uses spatial walk-off polarizers at the inputs and outputs. (a) Propagation from left to right. (b) Propagation from right to left.

2.3 Multiplexers and Filters

In this section, we will study the principles underlying the operation of a variety of wavelength selection technologies. Optical filters are essential components in transmission systems for at least two applications: to multiplex and demultiplex wavelengths in a WDM system—these devices are called multiplexers/demultiplexers—and to provide equalization of the gain and filtering of noise in optical amplifiers. Furthermore, understanding optical filtering is essential to understanding the operation of lasers later in this chapter.

The different applications of optical filters are shown in Figure 3.6. A simple filter is a two-port device that selects one wavelength and rejects all others. It may have an additional third port on which the rejected wavelengths can be obtained. A multiplexer combines signals at different wavelengths on its input ports onto a common output port, and a demultiplexer performs the opposite function. Multiplexers and demultiplexers are used in WDM terminals as well as in larger *wavelength crossconnects* and *wavelength add/drop multiplexers*.

Demultiplexers and multiplexers can be cascaded to realize *static* wavelength crossconnects (WXCs). In a static WXC, the crossconnect pattern is fixed at the time

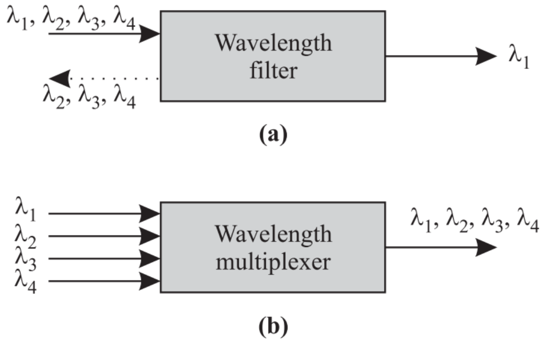

Figure 3.6 Different applications for optical filters in optical networks. (a) A simple filter, which selects one wavelength and either blocks the remaining wavelengths or makes them available on a third port. (b) A multiplexer, which combines multiple wavelengths into a single fiber. In the reverse direction, the same device acts as a demultiplexer to separate the different wavelengths.

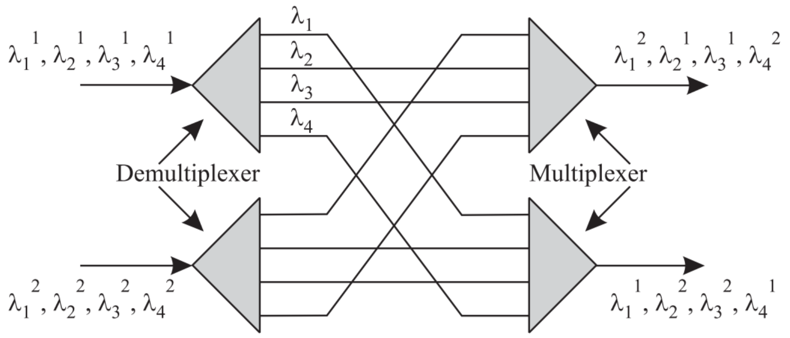

Figure 3.7 A static wavelength crossconnect. The device routes signals from an input port to an output port based on the wavelength.

the device is made and cannot be changed dynamically. Figure 3.7 shows an example of a static WXC. The device routes signals from an input port to an output port based on the wavelength. *Dynamic* WXCs can be constructed by combining optical switches with multiplexers and demultiplexers. Static WXCs are highly limited in terms of their functionality. For this reason, the devices of interest are dynamic rather than static WXCs. We will study different dynamic WXC architectures in Chapter 7.

A variety of optical filtering technologies are available. Their key characteristics for use in systems are the following:

1. Good optical filters should have low *insertion losses*. The insertion loss is the input-to-output loss of the filter.
2. The loss should be independent of the state of polarization of the input signals. The state of polarization varies randomly with time in most systems, and if the filter has a polarization-dependent loss, the output power will vary with time as well—an undesirable feature.
3. The passband of a filter should be insensitive to variations in ambient temperature. The *temperature coefficient* is measured by the amount of wavelength shift per unit degree change in temperature. The system requirement is that over the entire operating temperature range (about 100°C typically), the wavelength shift should be much less than the wavelength spacing between adjacent channels in a WDM system.
4. As more and more filters are cascaded in a WDM system, the passband becomes progressively narrower. To ensure reasonably broad passbands at the end of the cascade, the individual filters should have very flat passbands, so as to accommodate small changes in operating wavelengths of the lasers over time. This is measured by the 1 dB bandwidth, as shown in Figure 3.8.
5. At the same time, the passband skirts should be sharp to reduce the amount of energy passed through from adjacent channels. This energy is seen as *crosstalk* and degrades the system performance. The crosstalk suppression, or *isolation* of the filter, which is defined as the relative power passed through from the adjacent channels, is an important parameter as well.

All the filters and multiplexers we study use the property of *interference* among optical waves. In addition, some filters, for example, gratings, use the *diffraction* property—light from a source tends to spread in all directions depending on the incident wavelength. Table 3.1 compares the performance of different filtering technologies.

Table 3.1 Comparison of passive wavelength multiplexing/demultiplexing technologies. A 16-channel system with 100 GHz channel spacing is assumed. Other key considerations include center wavelength accuracy and manufacturability. All these approaches face problems in scaling with the number of wavelengths. TFMF is the dielectric thin-film multicavity filter, and AWG is the arrayed waveguide grating. For the fiber Bragg grating and the arrayed waveguide grating, the temperature coefficient can be reduced to 0.001 nm/°C by passive temperature compensation. The fiber Bragg grating is a single channel filter, and multiple filters need to be cascaded in series to demultiplex all 16 channels.

Filter Property	Fiber Bragg Grating	TFMF	AWG	Stimax Grating
1 dB BW (nm)	0.3	0.4	0.22	0.1
Isolation (dB)	25	25	25	30
Loss (dB)	0.2	7	5.5	6
PDL (dB)	0	0.2	0.5	0.1
Temp. coeff. (nm/°C)	0.01	0.0005	0.01	0.01