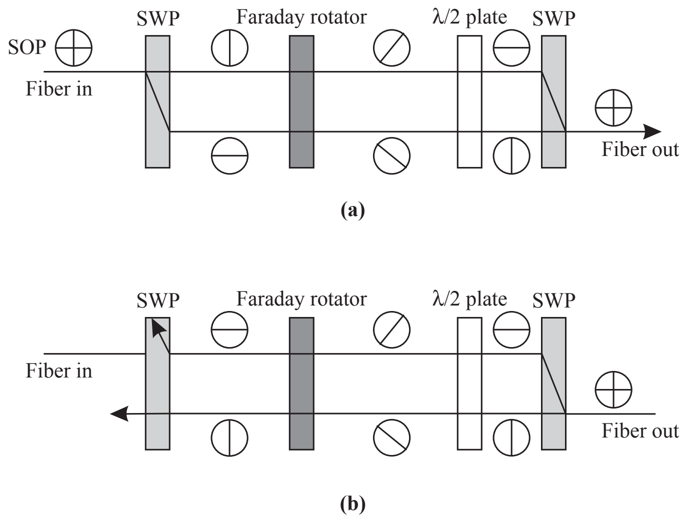

Figure 3.5 A polarization-independent isolator. The isolator is constructed along the same lines as a polarization-dependent isolator but uses spatial walk-off polarizers at the inputs and outputs. (a) Propagation from left to right. (b) Propagation from right to left.

3.3 *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

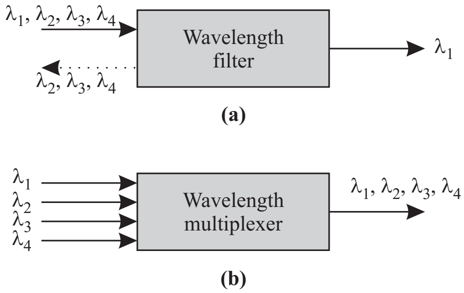

Figure 3.6 Different applications for optical filters in optical networks. (a) A simple filter, which selects one wavelength and either blocks the remaining wavelengths or makes them available on a third port. (b) A multiplexer, which combines multiple wavelengths into a single fiber. In the reverse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

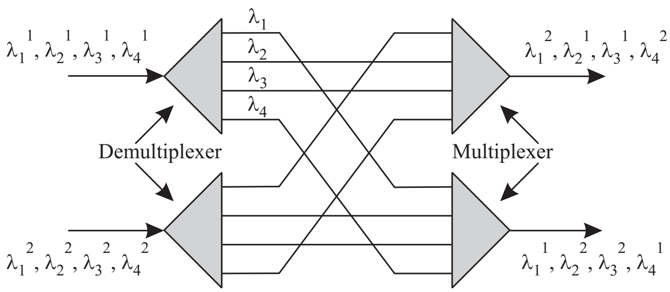

Figure 3.7 A static wavelength crossconnect. The device routes signals from an input port to an output port based on the wavelength.

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.

In addition to all the performance parameters described, perhaps the most important consideration is cost. Technologies that require careful hand assembly tend to be more expensive. There are two ways of reducing the cost of optical filters. The first is to fabricate them using integrated-optic waveguide technology. This is analogous to semiconductor chips, although the state of integration achieved with optics is significantly less. These waveguides can be made on many substrates, including silica, silicon, InGaAs, and polymers. Waveguide devices tend to be inherently polarization dependent due to the geometry of the waveguides, and care must be taken to reduce the PDL in these devices. The second method is to realize all-fiber devices. Such devices are amenable to mass production and are inherently polarization independent. It is also easy to couple light in and out of these devices from/into other fibers. Both of these approaches are being pursued today.

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

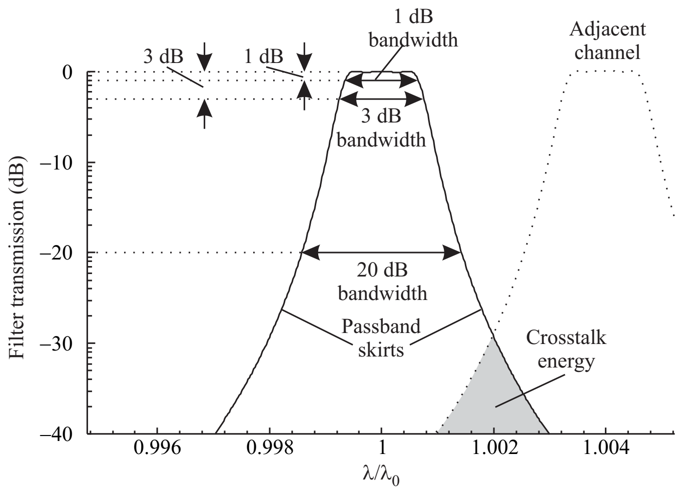

Figure 3.8 Characterization of some important spectral-shape parameters of optical filters. λ_0 is the center wavelength of the filter, and λ denotes the wavelength of the light signal.

incident wavelength. Table 3.1 compares the performance of different filtering technologies.

3.3.1 Gratings

The term *grating* is used to describe almost any device whose operation involves interference among multiple optical signals originating from the same source but with different relative *phase shifts*. An exception is a device where the multiple optical signals are generated by repeated traversals of a single cavity; such devices are called *etalons*. An electromagnetic wave (light) of angular frequency ω propagating, say, in the z direction has a dependence on z and t of the form $\cos(\omega t - \beta z)$. Here, β is the propagation constant and depends on the medium. The *phase* of the wave is $\omega t - \beta z$. Thus a relative phase shift between two waves from the same source can be achieved if they traverse two paths of different lengths.

Two examples of gratings are shown in Figure 3.9(a) and (b). Gratings have been widely used for centuries in optics to separate light into its constituent wavelengths. In WDM communication systems, gratings are used as demultiplexers to separate the individual wavelengths or as multiplexers to combine them. The Stimax grating of Table 3.1 is a grating of the type we describe in this section.