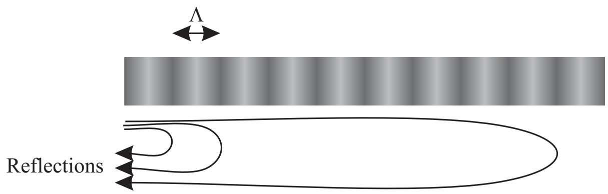

Figure 3.13 Principle of operation of a Bragg grating.

which result in a sinc(.) behavior for the side lobes. Apodization can be achieved by gradually starting and ending the grating. This technique is similar to pulse shaping used in digital communication systems to reduce the side lobes in the transmitted spectrum of the signal.

The bandwidth of the grating, which can be measured, for example, by the width of the main lobe, is inversely proportional to the length of the grating. Typically, the grating is a few millimeters long in order to achieve a bandwidth of 1 nm.

3.3.4 Fiber Gratings

Fiber gratings are attractive devices that can be used for a variety of applications, including filtering, add/drop functions, and compensating for accumulated dispersion in the system. Being all-fiber devices, their main advantages are their low loss, ease of coupling (with other fibers), polarization insensitivity, low temperature-coefficient, and simple packaging. As a result, they can be extremely low-cost devices.

Gratings are written in fibers by making use of the *photosensitivity* of certain types of optical fibers. A conventional silica fiber doped with germanium becomes extremely photosensitive. Exposing this fiber to ultraviolet (UV) light causes changes in the refractive index within the fiber core. A grating can be written in such a fiber by exposing its core to two interfering UV beams. This causes the radiation intensity to vary periodically along the length of the fiber. Where the intensity is high, the refractive index is increased; where it is low, the refractive index is unchanged. The change in refractive index needed to obtain gratings is quite small—around 10^{-4}. Other techniques, such as *phase masks,* can also be used to produce gratings. A phase mask is a diffractive optical element. When it is illuminated by a light beam, it splits the beams into different diffractive orders, which then interfere with one another to write the grating into the fiber.

Fiber gratings are classified as either *short-period* or *long-period* gratings, based on the period of the grating. Short-period gratings are also called Bragg gratings and have periods that are comparable to the wavelength, typically around 0.5 μm. We discussed the behavior of Bragg gratings in Section 3.3.3. Long-period gratings, on the other hand, have periods that are much greater than the wavelength, ranging from a few hundred micrometers to a few millimeters.

Fiber Bragg Gratings

Fiber Bragg gratings can be fabricated with extremely low loss (0.1 dB), high wavelength accuracy ($\pm$ 0.05 nm is easily achieved), high adjacent channel crosstalk suppression (40 dB), as well as flat tops.

The temperature coefficient of a fiber Bragg grating is typically 1.25×10^{-2} nm/°C due to the variation in fiber length with temperature. However, it is possible to compensate for this change by packaging the grating with a material that has a negative thermal expansion coefficient. These passively temperature-compensated gratings have temperature coefficients of around 0.07×10^{-2} nm/°C. This implies a very small 0.07 nm center wavelength shift over an operating temperature range of 100°C, which means that they can be operated without any active temperature control.

These properties of fiber Bragg gratings make them very useful devices for system applications. Fiber Bragg gratings are finding a variety of uses in WDM systems, ranging from filters and optical add/drop elements to dispersion compensators. A simple optical drop element based on fiber Bragg gratings is shown in Figure 3.14(a). It consists of a three-port circulator with a fiber Bragg grating. The circulator transmits light coming in on port 1 out on port 2 and transmits light coming in on port 2 out on port 3. In this case, the grating reflects the desired wavelength λ_2, which is then dropped at port 3. The remaining three wavelengths are passed through. It is possible to implement an add/drop function along the same lines, by introducing a coupler to add the same wavelength that was dropped, as shown in Figure 3.14(b). Many variations of this simple add/drop element can be realized by using gratings in combination with couplers and circulators. A major concern in these designs is that the reflection of these gratings is not perfect, and as a result, some power at the selected wavelength leaks through the grating. This can cause undesirable crosstalk, and we will study this effect in Chapter 5.

Fiber Bragg gratings can also be used to compensate for dispersion accumulated along the link. We will study this application in Chapter 5 in the context of dispersion compensation.

Long-Period Fiber Gratings

Long-period fiber gratings are fabricated in the same manner as fiber Bragg gratings and are used today primarily as filters inside erbium-doped fiber amplifiers to compensate for their nonflat gain spectrum. As we will see, these devices serve as very

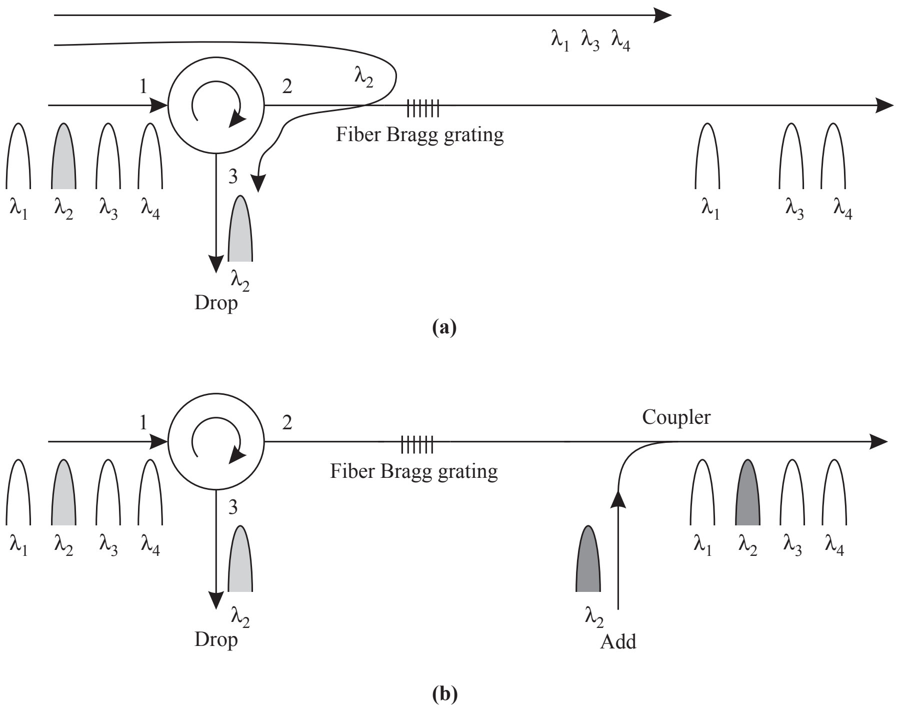

Figure 3.14 Optical add/drop elements based on fiber Bragg gratings. (a) A drop element. (b) A combined add/drop element.

efficient band rejection filters and can be tailored to provide almost exact equalization of the erbium gain spectrum. Figure 3.15 shows the transmission spectrum of such a grating. These gratings retain all the attractive properties of fiber gratings and are expected to become widely used for several filtering applications.

Principle of Operation

These gratings operate on somewhat different principles than Bragg gratings. In fiber Bragg gratings, energy from the forward propagating mode in the fiber core at the right wavelength is coupled into a backward propagating mode. In long-period gratings, energy is coupled from the forward propagating mode in the fiber core onto other forward propagating modes in the cladding. These cladding modes are extremely lossy, and their energy decays rapidly as they propagate along the fiber, due to losses at the cladding–air interface and due to microbends in the fiber. There are many cladding modes, and coupling occurs between a core mode at a given

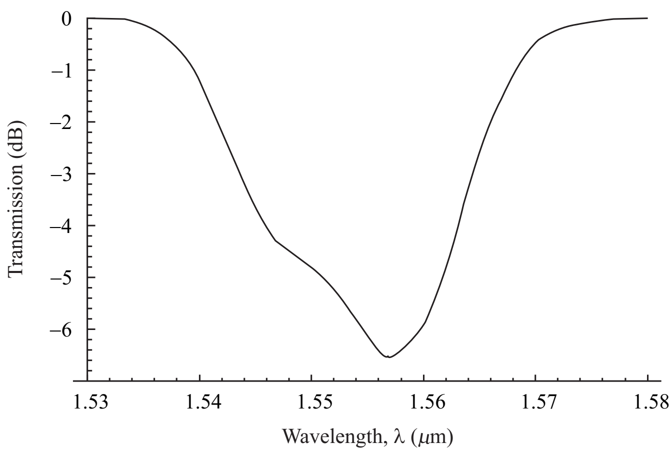

Figure 3.15 Transmission spectrum of a long-period fiber Bragg grating used as a gain equalizer for erbium-doped fiber amplifiers. (After [Ven96a].)

wavelength and a cladding mode depending on the pitch of the grating Λ, as follows: if β denotes the propagation constant of the mode in the core (assuming a single-mode fiber) and β_{cl}^p that of the pth-order cladding mode, then the phase-matching condition dictates that

$$\beta - \beta_{\mathrm{cl}}^p = \frac{2\pi}{\Lambda}.$$

In general, the difference in propagation constants between the core mode and any one of the cladding modes is quite small, leading to a fairly large value of Λ in order for coupling to occur. This value is usually a few hundred micrometers. (Note that in Bragg gratings the difference in propagation constants between the forward and backward propagating modes is quite large, leading to a small value for Λ, typically around 0.5 μm.) If n_{eff} and n_{eff}^p denote the effective refractive indices of the core and pth-order cladding modes, then the wavelength at which energy is coupled from the core mode to the cladding mode can be obtained as

$$\lambda = \Lambda(n_{\mathrm{eff}} - n_{\mathrm{eff}}^p),$$

where we have used the relation $\beta = 2\pi n_{\mathrm{eff}}/\lambda$.

Therefore, once we know the effective indices of the core and cladding modes, we can design the grating with a suitable value of Λ so as to cause coupling of energy out of a desired wavelength band. This causes the grating to act as a wavelength-dependent loss element. Methods for calculating the propagation

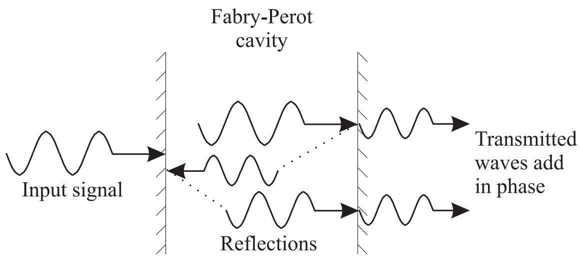

Figure 3.16 Principle of operation of a Fabry-Perot filter.

constants for the cladding modes are discussed in [Ven96b]. The amount of wavelength-dependent loss can be controlled during fabrication by controlling the UV exposure time. Complicated transmission spectra can be obtained by cascading multiple gratings with different center wavelengths and different exposures. The example shown in Figure 3.15 was obtained by cascading two such gratings [Ven96a]. These gratings are typically a few centimeters long.

3.3.5 Fabry-Perot Filters

A Fabry-Perot filter consists of the cavity formed by two highly reflective mirrors placed parallel to each other, as shown in Figure 3.16. This filter is also called a Fabry-Perot interferometer or etalon. The input light beam to the filter enters the first mirror at right angles to its surface. The output of the filter is the light beam leaving the second mirror.

This is a classical device that has been used widely in interferometric applications. Fabry-Perot filters have been used for WDM applications in several optical network testbeds. There are better filters today, such as the thin-film resonant multicavity filter that we will study in Section 3.3.6. These latter filters can be viewed as Fabry-Perot filters with wavelength-dependent mirror reflectivities. Thus the fundamental principle of operation of these filters is the same as that of the Fabry-Perot filter. The Fabry-Perot cavity is also used in lasers (see Section 3.5.1).

Compact Fabry-Perot filters are commercially available components. Their main advantage over some of the other devices is that they can be tuned to select different channels in a WDM system, as discussed later.

Principle of Operation

The principle of operation of the device is illustrated in Figure 3.16. The input signal is incident on the left surface of the cavity. After one pass through the cavity, as