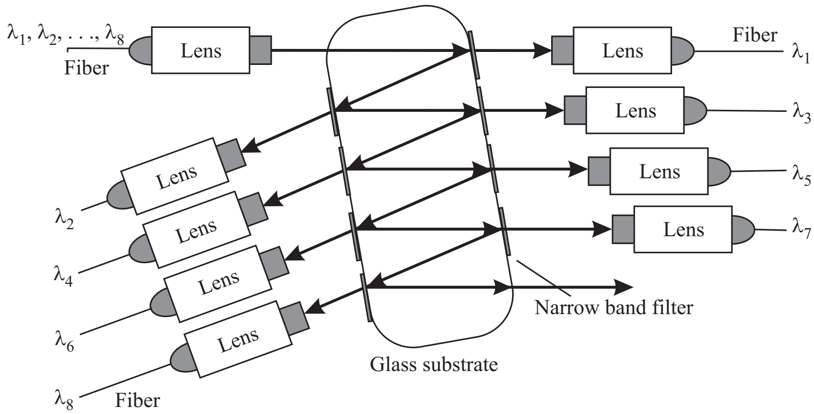

Figure 3.20 A wavelength multiplexer/demultiplexer using multilayer dielectric thin-film filters. (After [SS96].)

passes one wavelength and reflects all the others onto the second filter. The second filter passes another wavelength and reflects the remaining ones, and so on.

This device has many features that make it attractive for system applications. It is possible to have a very flat top on the passband and very sharp skirts. The device is extremely stable with regard to temperature variations, has low loss, and is insensitive to the polarization of the signal. Typical parameters for a 16-channel multiplexer are shown in Table 3.1. For these reasons, TFMFs are becoming widely used in commercial systems today. Understanding the principle of operation of these devices requires some knowledge of electromagnetic theory, and so we defer this to Appendix G.

3.3.7 *Mach-Zehnder Interferometers*

A Mach-Zehnder interferometer (MZI) is an interferometric device that makes use of two interfering paths of different lengths to resolve different wavelengths. Devices constructed on this principle have been around for some decades. Today, Mach-Zehnder interferometers are typically constructed in integrated optics and consist of two 3 dB directional couplers interconnected through two paths of differing lengths, as shown in Figure 3.21(a). The substrate is usually silicon, and the waveguide and cladding regions are silica (SiO_2).

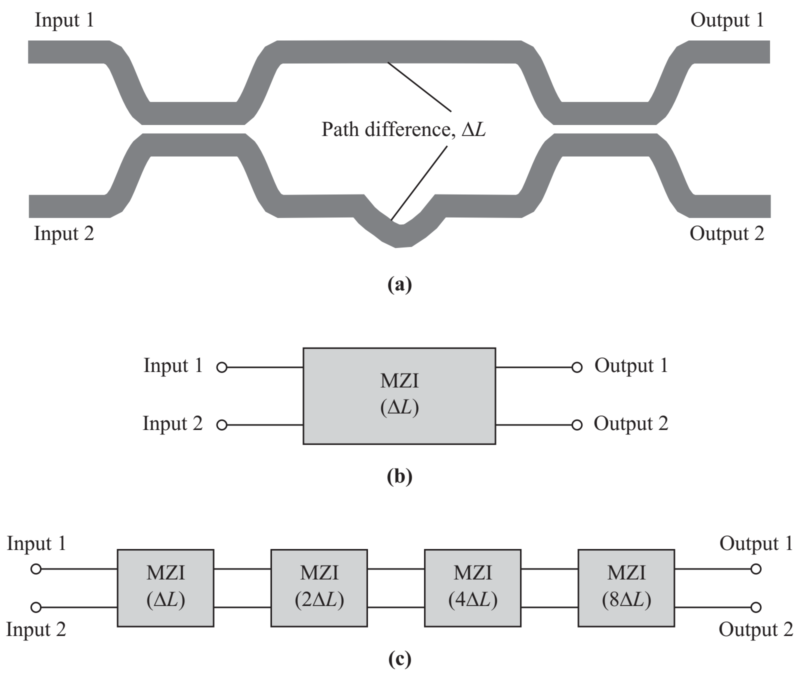

Figure 3.21 (a) An MZI constructed by interconnecting two 3 dB directional couplers. (b) A block diagram representation of the MZI in (a). ΔL denotes the path difference between the two arms. (c) A block diagram of a four-stage Mach-Zehnder interferometer, which uses different path length differences in each stage.

Mach-Zehnder interferometers are useful as both filters and (de)multiplexers. Even though there are better technologies for making narrow band filters, for example, dielectric multicavity thin-film filters, MZIs are still useful in realizing wide band filters. For example, MZIs can be used to separate the wavelengths in the 1.3 μm and 1.55 μm bands. Narrow band MZI filters are fabricated by cascading a number of stages, as we will see, and this leads to larger losses. In principle, very good crosstalk performance can be achieved using MZIs if the wavelengths are spaced such that the undesired wavelengths occur at, or close to, the nulls of the power transfer function. However, in practice, the wavelengths cannot be fixed precisely (for example, the wavelengths drift because of temperature variations or age). Moreover, the coupling ratio of the directional couplers is not 50:50 and could be wavelength dependent. As a result, the crosstalk performance is far from the ideal situation. Also the passband of narrow band MZIs is not flat. In contrast, the dielectric multicavity thin-film filters can have flat passbands and good stop bands.

MZIs are useful as two-input, two-output multiplexers and demultiplexers. They can also be used as tunable filters, where the tuning is achieved by varying the temperature of one of the arms of the device. This causes the refractive index of that arm to change, which in turn affects the phase relationship between the two arms and causes a different wavelength to be coupled out. The tuning time required is of the order of several milliseconds. For higher channel-count multiplexers and demultiplexers, better technologies are available today. One example is the *arrayed waveguide grating* (AWG) described in the next section. Since understanding the MZI is essential to understanding the AWG, we will now describe the principle of operation of MZIs.

Principle of Operation

Consider the operation of the MZI as a demultiplexer; so only one input, say, input 1, has a signal (see Figure 3.21(a)). After the first directional coupler, the input signal power is divided equally between the two arms of the MZI, but the signal in one arm has a phase shift of $\pi/2$ with respect to the other. Specifically, the signal in the lower arm lags the one in the upper arm in phase by $\pi/2$, as discussed in Section 3.1. This is best understood from (3.1). Since there is a length difference of ΔL between the two arms, there is a further phase lag of $\beta\Delta L$ introduced in the signal in the lower arm. In the second directional coupler, the signal from the lower arm undergoes another phase delay of $\pi/2$ in going to the first output relative to the signal from the upper arm. Thus the total relative phase difference at the first or upper output between the two signals is $\pi/2 + \beta\Delta L + \pi/2$. At the output directional coupler, in going to the second output, the signal from the upper arm lags the signal from the lower arm in phase by $\pi/2$. Thus the total relative phase difference at the second or lower output between the two signals is $\pi/2 + \beta\Delta L - \pi/2 = \beta\Delta L$.

If $\beta\Delta L = k\pi$ and k is odd, the signals at the first output add in phase, whereas the signals at the second output add with opposite phases and thus cancel each other. Thus the wavelengths passed from the first input to the first output are those wavelengths for which $\beta\Delta L = k\pi$ and k is odd. The wavelengths passed from the first input to the second output are those wavelengths for which $\beta\Delta L = k\pi$ and k is even. This could have been easily deduced from the transfer function of the MZI in the following equation (3.14), but this detailed explanation will help in the understanding of the arrayed waveguide grating (Section 3.3.8).

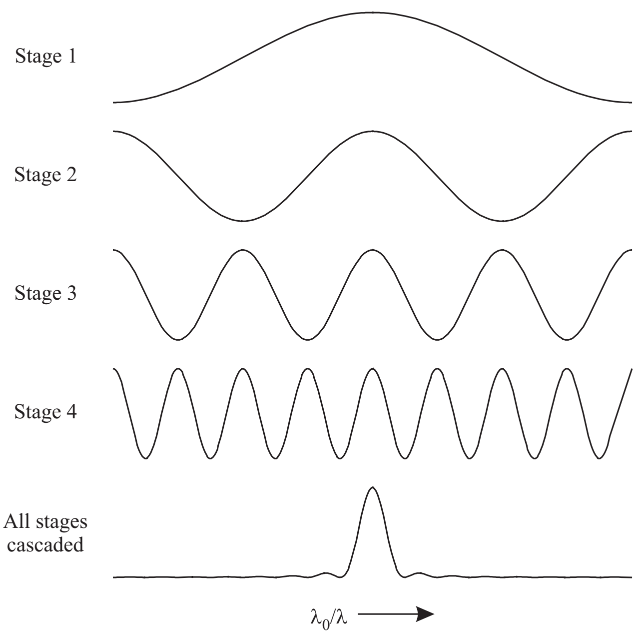

Figure 3.22 Transfer functions of each stage of a multistage MZI.

Assume that the difference between these path lengths is ΔL and that only one input, say, input 1, is active. Then it can be shown (see Problem 3.14) that the power transfer function of the Mach-Zehnder interferometer is given by

$$\begin{pmatrix} T_{11}(f) \\ T_{12}(f) \end{pmatrix} = \begin{pmatrix} \sin^2(\beta \Delta L/2) \\ \cos^2(\beta \Delta L/2) \end{pmatrix}. \tag{3.14}$$

Thus the path difference between the two arms, ΔL, is the key parameter characterizing the transfer function of the MZI. We will represent the MZI of Figure 3.21(a) using the block diagram of Figure 3.21(b).

Now consider k MZIs interconnected, as shown in Figure 3.21(c) for $k = 4$. Such a device is termed a *multistage Mach-Zehnder interferometer.* The path length difference for the kth MZI in the cascade is assumed to be $2^{k-1}\Delta L$. The transfer function of each MZI in this multistage MZI together with the power transfer function of the entire filter is shown in Figure 3.22. The power transfer function of the multistage MZI is also shown on a decibel scale in Figure 3.23.

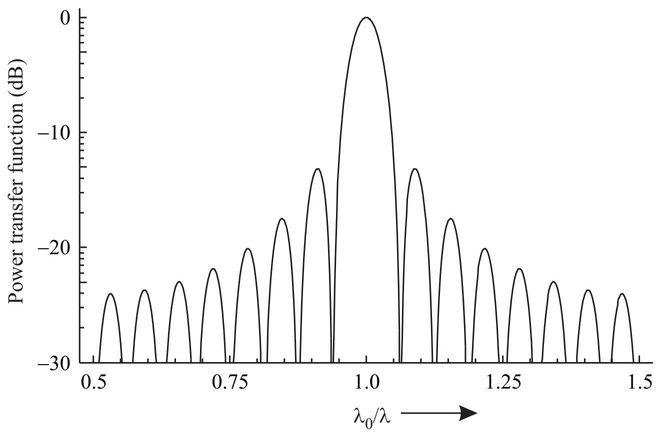

Figure 3.23 Transfer function of a multistage Mach-Zehnder interferometer.

We will now describe how an MZI can be used as a 1×2 demultiplexer. Since the device is reciprocal, it follows from the principles of electromagnetics that if the inputs and outputs are interchanged, it will act as a 2×1 multiplexer.

Consider a single MZI with a fixed value of the path difference ΔL. Let one of the inputs, say, input 1, be a wavelength division multiplexed signal with all the wavelengths chosen to coincide with the peaks or troughs of the transfer function. For concreteness, assume the propagation constant $\beta = 2\pi n_{\text{eff}}/\lambda$, where n_{eff} is the effective refractive index of the waveguide. The input wavelengths λ_i would have to be chosen such that $n_{\text{eff}}\Delta L/\lambda_i = m_i/2$ for some positive integer m_i. The wavelengths λ_i for which m is odd would then appear at the first output (since the transfer function is $\sin^2(m_i\pi/2)$), and the wavelengths for which m_i is even would appear at the second output (since the transfer function is $\cos^2(m_i\pi/2)$).

If there are only two wavelengths, one for which m_i is odd and the other for which m_i is even, we have a 1×2 demultiplexer. The construction of a $1 \times n$ demultiplexer when n is a power of two, using $n - 1$ MZIs, is left as an exercise (Problem 3.15). But there is a better method of constructing higher channel count demultiplexers, which we describe next.

3.3.8 Arrayed Waveguide Grating

An *arrayed waveguide grating* (AWG) is a generalization of the Mach-Zehnder interferometer. This device is illustrated in Figure 3.24. It consists of two multiport