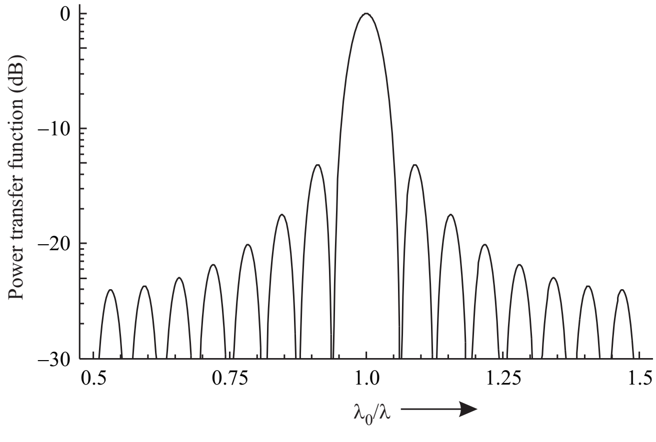

Figure 3.23 Transfer function of a multistage Mach-Zehnder interferometer.

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 couplers interconnected by an array of waveguides. The MZI can be viewed as a device where *two* copies of the same signal, but shifted in phase by different amounts, are added together. The AWG is a device where *several* copies of the same signal, but shifted in phase by different amounts, are added together.

The AWG has several uses. It can be used as an $n \times 1$ *wavelength multiplexer.* In this capacity, it is an n-input, 1-output device where the n inputs are signals at different wavelengths that are combined onto the single output. The inverse of this function, namely, $1 \times n$ *wavelength demultiplexing,* can also be performed using an AWG. Although these wavelength multiplexers and demultiplexers can also be built using MZIs interconnected in a suitable fashion, it is preferable to use an AWG. Relative to an MZI chain, an AWG has lower loss and flatter passband, and is easier to realize on an integrated-optic substrate. The input and output waveguides, the multiport couplers, and the arrayed waveguides are all fabricated on a single substrate. The substrate material is usually silicon, and the waveguides are silica, Ge-doped silica, or SiO_2-Ta_2O_5. Thirty-two–channel AWGs are commercially available, and smaller AWGs are being used in WDM transmission systems. Their temperature coefficient (0.01 nm/°C) is not as low as those of some other competing technologies such as fiber gratings and multilayer thin-film filters. So we will need to use active temperature control for these devices.

Another way to understand the working of the AWG as a demultiplexer is to think of the multiport couplers as lenses and the array of waveguides as a prism. The input coupler collimates the light from an input waveguide to the array of waveguides. The array of waveguides acts like a prism, providing a wavelength-dependent phase shift, and the output coupler focuses different wavelengths on different output waveguides.

The AWG can also be used as a static wavelength crossconnect. However, this wavelength crossconnect is not capable of achieving an arbitrary routing pattern. Although several interconnection patterns can be achieved by a suitable choice of

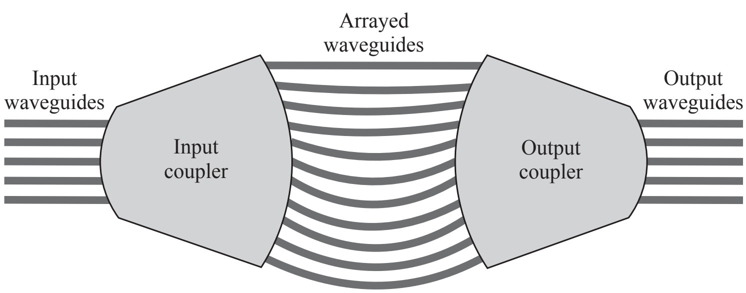

Figure 3.24 An arrayed waveguide grating.

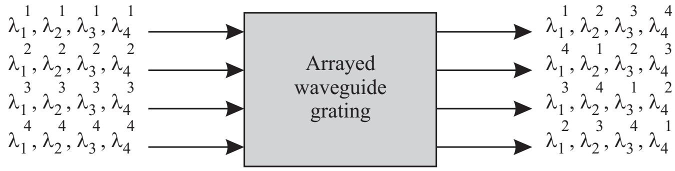

Figure 3.25 The crossconnect pattern of a static wavelength crossconnect constructed from an arrayed waveguide grating. The device routes signals from an input to an output based on their wavelength.

the wavelengths and the FSR of the device, the most useful one is illustrated in Figure 3.25. This figure shows a 4×4 static wavelength crossconnect using four wavelengths with one wavelength routed from each of the inputs to each of the outputs.

In order to achieve this interconnection pattern, the operating wavelengths and the FSR of the AWG must be chosen suitably. The FSR of the AWG is derived in Problem 3.17. Given the FSR, we leave the determination of the wavelengths to be used to achieve this interconnection pattern as another exercise (Problem 3.18).

Principle of Operation

Consider the AWG shown in Figure 3.24. Let the number of inputs and outputs of the AWG be denoted by n. Let the couplers at the input and output be $n \times m$ and $m \times n$ in size, respectively. Thus the couplers are interconnected by m waveguides. We will call these waveguides *arrayed waveguides* to distinguish them from the input and output waveguides. The lengths of these waveguides are chosen such that the difference in length between consecutive waveguides is a constant denoted by ΔL. The MZI is a special case of the AWG, where $n = m = 2$. We will now determine which wavelengths will be transmitted from a given input to a given output. The first coupler splits the signal into m parts. The relative phases of these parts are determined by the distances traveled in the coupler from the input waveguides to the arrayed waveguides. Denote the differences in the distances traveled (relative to any one of the input waveguides and any one of the arrayed waveguides) between input waveguide i and arrayed waveguide k by d_{ik}^{in}. Assume that arrayed waveguide k has a path length larger than arrayed waveguide $k-1$ by ΔL. Similarly, denote the differences in the distances traveled (relative to any one of the arrayed waveguides and any one of the output waveguides) between arrayed waveguide k and output waveguide j by d_{kj}^{out}. Then, the relative phases of the signals from input i to output j traversing the m different paths between them are given by

$$\phi_{ijk} = \frac{2\pi}{\lambda}(n_1 d_{ik}^{\text{in}} + n_2 k \Delta L + n_1 d_{kj}^{\text{out}}), \qquad k = 1, \ldots, m. \tag{3.15}$$

Here, n_1 is the refractive index in the input and output directional couplers, and n_2 is the refractive index in the arrayed waveguides. From input i, those wavelengths λ, for which ϕ_{ijk}, $k = 1, \ldots, m$, differ by a multiple of 2π will add in phase at output j. The question is, Are there any such wavelengths?

If the input and output couplers are designed such that $d_{ik}^{\text{in}} = d_i^{\text{in}} + k\delta_i^{\text{in}}$ and $d_{kj}^{\text{out}} = d_j^{\text{out}} + k\delta_j^{\text{out}}$, then (3.15) can be written as

$$\begin{aligned} \phi_{ijk} &= \frac{2\pi}{\lambda}(n_1 d_i^{\text{in}} + n_1 d_j^{\text{out}}) \\ &\quad + \frac{2\pi k}{\lambda}(n_1 \delta_i^{\text{in}} + n_2 \Delta L + n_1 \delta_j^{\text{out}}), \qquad k = 1, \ldots, m. \end{aligned} \tag{3.16}$$

Such a construction is possible and is called the *Rowland circle construction*. It is illustrated in Figure 3.26 and discussed further in Problem 3.16. Thus wavelengths λ that are present at input i and that satisfy $n_1 \delta_i^{\text{in}} + n_2 \Delta L + n_1 \delta_j^{\text{out}} = p\lambda$ for some integer p add in phase at output j.

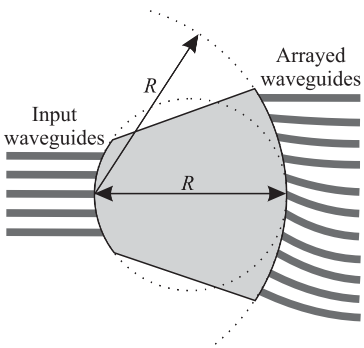

Figure 3.26 The Rowland circle construction for the couplers used in the AWG. The arrayed waveguides are located on the arc of a circle, called the *grating circle*, whose center is at the end of the central input (output) waveguide. Let the *radius* of this circle be denoted by R. The other input (output) waveguides are located on the arc of a circle whose *diameter* is equal to R; this circle is called the *Rowland circle*. The vertical spacing between the arrayed waveguides is chosen to be constant.

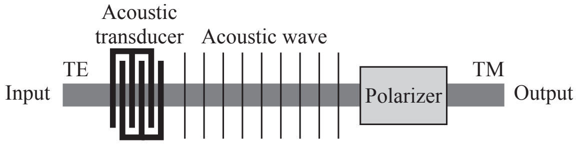

Figure 3.27 A simple AOTF. An acoustic wave introduces a grating whose pitch depends on the frequency of the acoustic wave. The grating couples energy from one polarization mode to another at a wavelength that satisfies the Bragg condition.

For use as a demultiplexer, all the wavelengths are present at the same input, say, input i. Therefore, if the wavelengths, $\lambda_1, \lambda_2, \ldots, \lambda_n$ in the WDM system satisfy $n_1\delta_i^{\text{in}} + n_2\Delta L + n_1\delta_j^{\text{out}} = p\lambda_j$ for some integer p, we infer from (3.16) that these wavelengths are demultiplexed by the AWG. Note that though δ_i^{in} and ΔL are necessary to define the precise set of wavelengths that are demultiplexed, the (minimum) spacing between them is independent of δ_i^{in} and ΔL, and determined primarily by δ_j^{out}.

Note in the preceding example that if wavelength λ'_j satisfies $n_1\delta_i^{\text{in}} + n_2\Delta L + n_1\delta_j^{\text{out}} = (p+1)\lambda'_j$, then both λ_j and λ'_j are "demultiplexed" to output j from input i. Thus like many of the other filter and multiplexer/demultiplexer structures we have studied, the AWG has a periodic response (in frequency), and all the wavelengths must lie within one FSR. The derivation of an expression for this FSR is left as an exercise (Problem 3.17).

3.3.9 Acousto-Optic Tunable Filter

The acousto-optic tunable filter is a versatile device. It is probably the only known *tunable* filter that is capable of selecting several wavelengths simultaneously. This capability can be used to construct a wavelength crossconnect, as we will explain later in this section.

The acousto-optic tunable filter (AOTF) is one example of several optical devices whose construction is based on the interaction of sound and light. Basically, an acoustic wave is used to create a Bragg grating in a waveguide, which is then used to perform the wavelength selection. Figure 3.27 shows a simple version of the AOTF. We will see that the operation of this AOTF is dependent on the state of polarization of the input signal. Figure 3.28 shows a more realistic polarization-independent implementation in integrated optics.