Silicon Photonics
矽光子學
A Selection of Photonic Devices (C)

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Outline

- 6.4 THE WAVEGUIDE-TO-WAVEGUIDE COUPLER (Directional Coupler)
- 6.5 THE ARRAYED WAVEGUIDE GRATING (AWG)
- 6.6 WAVEGUIDE COUPLERS FOR SMALL-DIMENSION WAVEGUIDES

6.4 THE WAVEGUIDE-TO-WAVEGUIDE COUPLER (Directional Coupler)

WAVEGUIDE-TO-WAVEGUIDE COUPLER (Directional Coupler)

- In Chapters 2 and 3 we saw that power propagating along a waveguide includes some power traveling outside the waveguide in the cladding.
- This was characterized in our planar waveguide by the penetration depth of the cladding.
- The field that extends beyond the waveguide is referred to as the *evanescent field.*
- We can use this field to couple light from one waveguide to another if the waveguides are sufficiently close that the evanescent fields overlap, in a device called a waveguide-to-waveguide coupler, or an evenescent coupler.
- Zappe presented a useful simpli-fied analysis of such a device, and we follow his approach here.

WAVEGUIDE-TO-WAVEGUIDE COUPLER (Directional Coupler)

- Consider the two identical waveguides, (a) and (b), shown in Figure 6.25.
- The waveguides have width *w,* and are separated by a small distance *s.*
- Let the field in waveguide (a) be described by the equation: $E_a = a_0(x, y)e^{j\beta z}e^{j\omega t}$

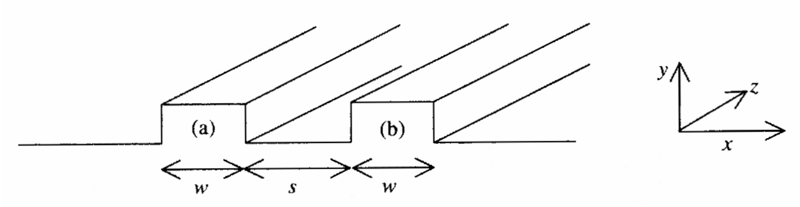

Figure 6.25 Two waveguides separated by a small distance *s.*

WAVEGUIDE-TO-WAVEGUIDE COUPLER (Directional Coupler)

- Similarly the field in waveguide (b) will be:

$$E_b = b_0(x, y)e^{j\beta z}e^{j\omega t}$$

- The way the fields interact can be described by coupled mode theory (see for example [12]).
- Simplified versions of the coupling equations that relate the amplitudes within each waveguide are:

$$\mathrm{d}a_0/\mathrm{d}z = \kappa b_0$$

$$\mathrm{d}b_0/\mathrm{d}z = -\kappa a_0$$

where κ is a coupling coefficient.

WAVEGUIDE-TO-WAVEGUIDE COUPLER (Directional Coupler)

- In these simplified equations we have assumed that the waveguides are identical and hence a phase match exists between the modes in each waveguide, no attenuation, and co-directional coupling.
- If we now assume that one of the waveguides is excited at $Z = 0$, and the other is not, then we have:

$$a_0(z = 0) = 0$$

$$b_0(z = 0) = c_0$$

- The solutions of these equations take the form:

$$a_0(z) = c_0 \sin(\kappa z)$$

$$b_0(z) = c_0 \cos(\kappa z)$$

WAVEGUIDE-TO-WAVEGUIDE COUPLER (Directional Coupler)

- Therefore it is clear that a field in one waveguide gives rise to a field in the other, over some propagation distance *z,* and further that the transfer of power from one guide to the other is periodic, with a period given by the coupling length, referred to as L_π.
- We can see that complete transfer of power from one guide to the other takes place when $L_\pi = m\pi/2\kappa$, for integer values of *m.*
- Therefore we can also imagine coupling lengths that are a specific fraction of the coupling length to couple a predetermined proportion of the power from one waveguide to the other.

WAVEGUIDE-TO-WAVEGUIDE COUPLER (Directional Coupler)

- A particularly common example is the coupler with coupling length $L_c = L_\pi/2 = m\pi/4\kappa$, which couples half of the energy from one waveguide to the other.
- This structure is known as the 3-dB coupler for obvious reasons.
- The fact that power transfers from one guide to another in a periodic manner means that over multiple coupling lengths the power will transfer back and forth between the waveguides.
- This means that if a single coupling length is very short, it may be more convenient to make devices with multiple coupling lengths, although care must be taken to ensure that fabrication tolerances are not exacerbated in this case.

WAVEGUIDE-TO-WAVEGUIDE COUPLER (Directional Coupler)

- The coupling efficiency is determined by the coupling coefficient, κ, which can be expressed as [13]:

$$\kappa = \frac{2k_{xc}^2 k_{xs} \exp(-k_{xs}s)}{\beta w(k_{xs}^2 + k_{xc}^2)} \qquad (6.30)$$

  where k_{xc} is the *x-directed* propagation constant in the core, k_{xs} is the *x-directed* decay constant (between the waveguides), w is the waveguide width, and s is the waveguide separation.
- The exponential term in equation 6.30 is clearly a strong influence on the value of κ.

WAVEGUIDE-TO-WAVEGUIDE COUPLER (Directional Coupler)

- This shows that the waveguide spacing and decay constant are very important parameters to the coupler.
- Clearly this is expected, as the degree to which the evanescent fields overlap is dependent upon these parameters.
- Equation 6.30 shows that the coupling coefficient is not only a function of modal confinement, but also of the propagation constant.
- This implies that coupling efficiency will vary with wavelength, and hence by cascading a series of couplers of slightly different design it is possible to achieve a specific wavelength dependence.

Applications of the Waveguide-to-Waveguide Coupler

- The waveguide-to-waveguide coupler is a fundamental device to a number of other devices.
- Firstly, consider a Mach-Zehnder interferometer formed with a waveguide-to-waveguide coupler replacing one or both of the waveguide Y-junctions.
- An example is shown in Figure 6.26.
- We have seen from section 6.4 that light will be in one or both of the output waveguides depending on the design of the coupler as well as the interaction length of the coupler.

Applications of the Waveguide-to-Waveguide Coupler

- Hence it is possible to design the coupler such that varying the phase of the optical wave results in switching from one output waveguide to the other, forming an optical switch.
- Furthermore, by also replacing the input Y-junction of the interferometer, a 2 x 2 switch would result.

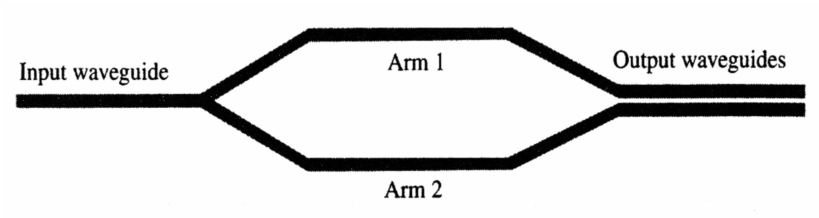

Figure 6.26 Waveguide-to-waveguide coupler at the output of a Mach-Zehnder interferometer

Applications of the Waveguide-to-Waveguide Coupler

- The waveguide-to-waveguide coupler can also be used as an input and/or output device for other devices.
- A ring resonator is one such example, shown in Figure 6.27.
- The input waveguide excites the resonator, by coupling a proportion of the input power to the ring.
- The device will then act as an interferometer, because after each revolution of the ring.

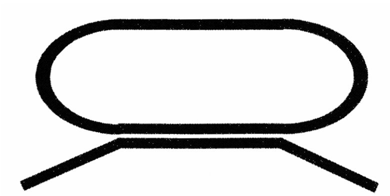

Figure 6.27 Waveguide-to-waveguide coupler forming part of an optical ring resonator

Applications of the Waveguide-to-Waveguide Coupler

- The light in the ring will be in phase with incoming light, only if the phase shift introduced by propagation around the ring, $\Delta\varphi$, is an integral number of wavelength periods; i.e.:

$$\Delta\phi = 2m\pi$$

$$\beta L = 2m\pi$$

where β is the waveguide propagation constant, *L* is the optical path length, and *m* is an integer.

Applications of the Waveguide-to-Waveguide Coupler

- Thus the device will be resonant for wavelengths that satisfy this condition. Substituting for the optical path length, $L = 2\pi R$, where *R* is the radius of the ring, and for β in terms of wavelength, we can write an expression for resonant wavelengths of the ring:

$$\lambda = \frac{2\pi NR}{m}$$

where *N* is the effective index of the waveguide mode.
- An additional coupler can be added at the opposite side of the ring resonator to obtain an output in antiphase to the first, since only half the phase shift is experience by one half revolution of the ring.

6.5 THE ARRAYED WAVEGUIDE GRATING (AWG)

ARRAYED WAVEGUIDE GRATING (AWG)

- The AWG is one of the most important integrated optical devices introduced in recent years.
- The device has proved to be very flexible, being utilized in a number of configurations including multiplexing of wavelengths, demultiplexing, switching and N x N routing, and as part of add-drop filter designs.
- This section is included to introduce the AWG, and provide a basic understanding of the operation of the device.
- Firstly however, it is helpful to consider the interference of a series of coherent light sources, as this will aid the understanding of the AWG.

Interference of *N* Coherent Light Sources

- Whilst the interference of several coherent sources will not fully describe the behavior of a diffraction grating, or the AWG, it is a useful starting point, as we can understand the ideas behind the AWG.
- This is a well-known interference problem.
- Consider a linear array of *N* identical oscillators, a distance *d* apart.
- Initially consider the oscillators to be both coherent and in phase, and of the same polarization.

Interference of *N* Coherent Light Sources

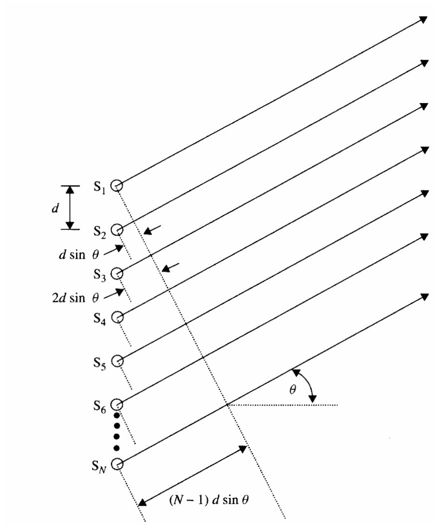

Figure 6.28 *N* coherent sources in a linear array.

Interference of *N* Coherent Light Sources

- Consider interference of the rays from all of the sources (S_1 to S_N) at some distant point, *P*.
- If the size of the array is small compared to the distance to *P*, the amplitude arriving at point *P* will be approximately the same from each source.
- Furthermore the rays from the sources will be approximately parallel arriving at the distant point *P*.

Interference of *N* Coherent Light Sources

- We can express each contribution to the electric field arriving at point *P* as:

$$E_i = E_0 \exp[j(\omega t - \beta r_i)]$$

- where the subscript *i* represents all sources from 1 to *N*, and *r* is the distance from each source to the point *P*. Therefore the total field arriving at *P*, E_t, is the sum of the individual contributions:

$$E_t = E_0 \exp[j(\omega t - \beta r_1)] + E_0 \exp[j(\omega t - \beta r_2)] + \cdots + E_0 \exp[j(\omega t - \beta r_N)]$$

Interference of *N* Coherent Light Sources

- It can be seen from Figure 6.28 that the additional path length, Δr, to *P* between successive sources is $d \sin\theta$.
- Therefore the additional phase shift, $\Delta\varphi$ at *P* from successive sources is:

$$\Delta\phi = -\beta\Delta r = -\beta d \sin\theta$$

- Therefore the total field at P may be rewritten as:

$$E_t = E_0 \exp[j(\omega t - \beta r_1)] \times [1 + \exp(j(\Delta\phi)) + \exp(j(2\Delta\phi)) + \cdots + \exp(j(N\Delta\phi))] \tag{6.37}$$

Interference of *N* Coherent Light Sources

- However, the term in the second square bracket is just a geometric series, so equation 6.37 reduces to:

$$\begin{aligned} E_t &= E_0 \exp[j(\omega t - \beta r_1)]\left[\frac{\exp(j(N\Delta\phi)) - 1}{\exp(j(\Delta\phi)) - 1}\right] \\ &= E_0 \exp[j(\omega t - \beta r_1)]\left[\frac{\exp(jN\Delta\phi/2)}{\exp(j\Delta\phi/2)}\right] \\ &\quad \times \left[\frac{\exp(jN\Delta\phi/2) - \exp(-jN\Delta\phi/2)}{\exp(j\Delta\phi/2) - \exp(-j\Delta\phi/2)}\right] \\ &= E_0 \exp[j(\omega t - \beta r_1)][\exp(j(N-1)\Delta\phi/2)] \\ &\quad \times \left[\frac{\exp(jN\Delta\phi/2) - \exp(-jN\Delta\phi/2)}{\exp(j\Delta\phi/2) - \exp(-j\Delta\phi/2)}\right] \\ &= E_0 \exp[j(\omega t - \beta r_1 + (N-1)\Delta\phi/2)]\left[\frac{\sin(N\Delta\phi/2)}{\sin(\Delta\phi/2)}\right] \end{aligned}$$

Interference of *N* Coherent Light Sources

- If we now consider the intensity at point *P*, which is proportional to $(E_t)^2$, we obtain:

$$I = I_0 \left[\frac{\sin^2(N\Delta\phi/2)}{\sin^2(\Delta\phi/2)} \right]$$

- where I_0 is the intensity from any single source arriving at *P*.
- We can also substitute for $\Delta\varphi$ in order to see the dependence on θ.

Interference of *N* Coherent Light Sources

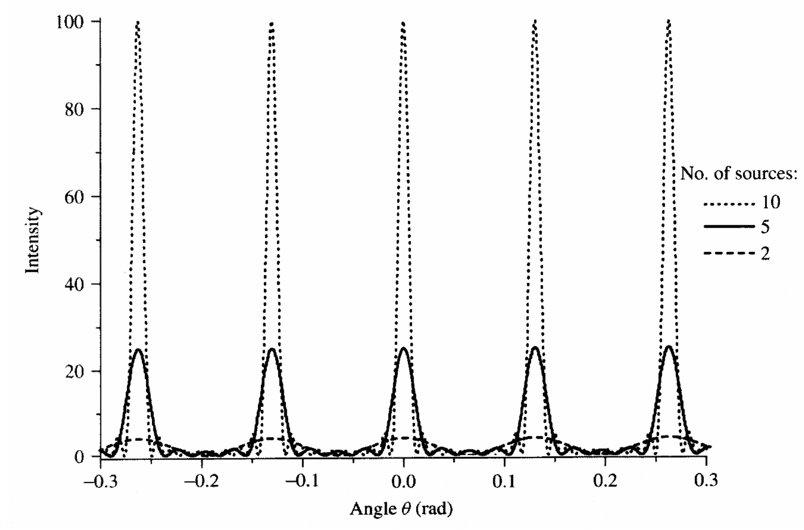

Figure 6.29 Intensity variations with number of sources N

Interference of *N* Coherent Light Sources

- Recalling from equation 6.36 that:

$$\Delta\phi = -\beta\Delta r = -\beta d \sin\theta$$

then equation 6.39 becomes:

$$I = I_0 \left[\frac{\sin^2[(N\beta d/2)\sin\theta]}{\sin^2[(\beta d/2)\sin\theta]} \right]$$

- We can plot equation 6.41 for various values of *N* (the number of sources), shown in Figure 6.29, for 2, 5 and 10 sources.

Interference of *N* Coherent Light Sources

- Clearly the principal peaks of the curve occur when $\Delta\varphi = 2m\pi$, which is a function of angle θ.
- These principal peaks increase in intensity with the square of the number of sources, as expected, because when $\Delta\varphi = 2m\pi$, equation 6.41 reduces to $I = N^2 I_0$.
- Notice that there are also subsidiary maxima between the principal peaks, owing to the rapid variations of the numerator in equation 6.41.

Interference of *N* Coherent Light Sources

- Let us now introduce an additional phase shift between adjacent sources.
- If we make the additional phase shift equivalent to a fixed change in path length, ΔL, then the phase shift will vary with wavelength of operation.
- This is because the phase shift is given by the propagation constant multiplied by the path length.
- For each wavelength, the propagation constant will be different, and hence the phase shift will be different.

Interference of *N* Coherent Light Sources

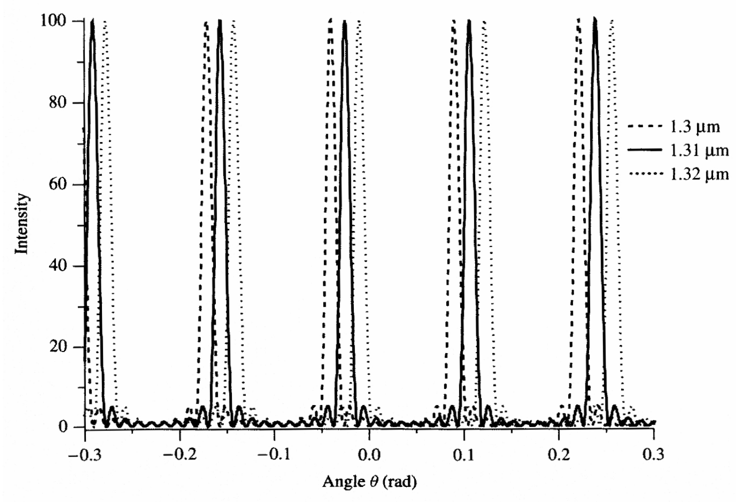

Figure 6.30 Addition of a fixed path length difference can separate wavelengths

Interference of *N* Coherent Light Sources

- Consider the effect on the interference pattern of an array of 10 sources, as shown in Figure 6.30.
- The first significant difference is that the principal maxima are no longer spaced symmetrically about an angle of $\theta = 0$.
- This means that introducing a successive phase shift to all sources can shift the position of the principal maxima.
- Secondly, when we introduce slightly different wavelengths, because the phase shift is slightly different in each case, the principal peaks occur at different positions.

Interference of *N* Coherent Light Sources

- In the case of no additional phase shift the principal peaks occurred when:

$$|\Delta\phi| = \beta d \sin\theta = 2m\pi$$

- When additional path length ΔL is included, the principal peaks now occur when:

$$|\Delta\phi| = \beta d \sin\theta + \beta\Delta L = 2m\pi$$

- Now that we have demonstrated that an increasing phase change across an array of coherent sources can result in separation of wave-lengths, let us consider the operation of the arrayed waveguide grat-ing itself.

Operation of the AWG

- The purpose of this section of the text is to give an explanation of the operation of the AWG.
- The most powerful operation of the AWG is the separation of wavelengths within an integrated optical device, so by way of example the operation of an AWG as a wavelength demultiplexer will be described.
- This section follows the approach of [15], to explain the outline operation of the AWG.
- The general layout is shown in Figure 6.31.

Operation of the AWG

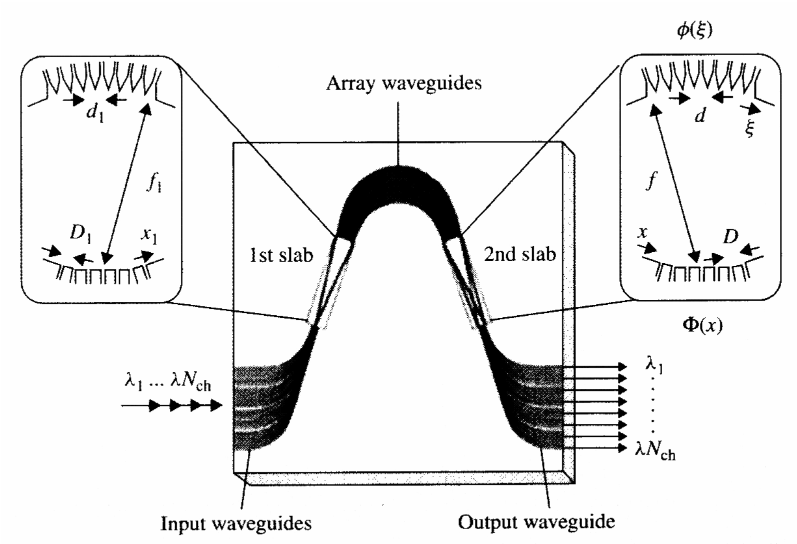

Figure 6.31 Configuration of a typical AWG layout.

Operation of the AWG

- It can be seen that the AWG comprises two planar regions which act as passive star couplers, and an array of rib waveguides, of progressively increasing length.
- The first planar region is used to excite the array of waveguides, and the second planar region is to allow multiple beam interference from the outputs of the array of waveguides.
- The array waveguides are included to introduce incremental phase shifts to the rays emerging from those waveguides.
- If a single wavelength is introduced into one of the input waveguides, this wavelength is distributed to the array waveguides.
- This wavelength propagates through these waveguides, each ray emerging with the incremental phase shift due to the length of the waveguide in question.

Operation of the AWG

- This is equivalent to introducing an incremental phase shift to the series of *N* coherent sources in section 6.5.1.
- In the second planar region the beams emerging from the array waveguides interfere to produce a pattern with a single principal peak, that spatially coincides with one of the output waveguides.
- If a second wavelength is introduced into the same input waveguide, it will also be distributed to the array of waveguides, but will experience a different phase shift through each of the waveguides, owing to the different propagation constant associated with each wavelength.
- Consequently the peak of the interference pattern of the second wavelength in the second planar region will occur at a different output waveguide, separating the two wavelengths.
- Multiple wavelengths can be separated in this way, producing a wavelength demultiplexer.

Operation of the AWG

- Let the array of rib waveguides have a constant path length difference, ΔL, between neighboring waveguides.
- In the first slab region, let the input waveguide separation be D_1, the array waveguide separation be d_1, and the radius of curvature be f_1.
- In general, the waveguide parameters in the first and the second slab regions do not have to be the same, therefore in the second slab region, let the output waveguide separation be D, the array waveguide separation be d, and the radius of curvature be f.
- Measuring the input position anticlockwise from the centre of the input waveguides as position x_1, the light is radiated to the first slab and then excites the arrayed waveguides.

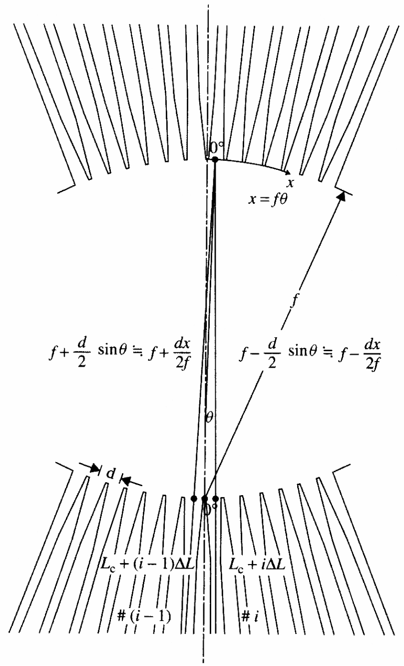

Figure 6.32 Enlarged view of the output optical slab of the A WG.

Operation of the AWG

- The excited electric field amplitude at each array waveguide is a_i (i = 1 to N), where N is the total number of array waveguides.
- The amplitude profile of a_i is typically a gaussian distribution (although more complex distributions can be more favorable).
- After traveling through the arrayed waveguides the light beams constructively interfere into one point x, measured in an anticlockwise direction from the centre of the output waveguides in the second slab, in the same way multiple beam interference was demonstrated in section 6.5.1.

Operation of the AWG

- Therefore, the position of this focal point depends on the operating wavelength and the relative phase delay in each waveguide, which is given by $\Delta L/\lambda$.
- If we consider the total phase delays for the two light rays passing through the $(i-1)^{th}$ and i^{th} array waveguides, the geometrical distances of the two beams in the second slab region are approximated as shown in Figure 6.32.
- The first slab will be of similar configuration, but may have different dimensions.
- The difference of the total phase delays for the two light rays passing through the $(i-1)^{th}$ and i^{th} array waveguides must be an integral multiple of 2π in order that the two beams constructively interfere at the focal point x.

Operation of the AWG

- Since the phase change is given by the propagation constant multiplied by the distance of propagation, if we assume identical propagation constants in each of the two slabs, then the interference condition is:

$$\beta_s\left(f_1 - \frac{d_1 x_1}{2f_1}\right) + \beta_c(L_c + (i-1)\Delta L) + \beta_s\left(f + \frac{dx}{2f}\right)$$
$$= \beta_s\left(f_1 + \frac{d_1 x_1}{2f_1}\right) + \beta_c(L_c + i\Delta L) + \beta_s\left(f - \frac{dx}{2f}\right) - 2m\pi$$

where β_s and β_c denote the propagation constants in the slab region and array waveguide, m is an integer, λ_0 is the centre wavelength of the WDM system, and L_c is the minimum array waveguide length.

Operation of the AWG

- Eliminating common terms we obtain:

$$\beta_s \frac{d_1 x_1}{f_1} - \beta_s \frac{dx}{f} + \beta_c \Delta L = 2m\pi \qquad (6.45)$$

- When the phase shift is a multiple of 2π, $\beta_c \, \Delta L = 2m\pi$. So:

$$\lambda_0 = \frac{N_c}{m}\Delta L \qquad (6.46)$$

- Then the light input position x_1 and the output position x will be related by:

$$\frac{d_1 x_1}{f_1} = \frac{dx}{f} \qquad (6.47)$$

Operation of the AWG

- In equation 6.46, N_c is the effective index of the array waveguides, and m is the *diffraction order.*
- Therefore, when light is coupled into the input position x_1 the output position x is determined by equation 6.47.
- Often the waveguide parameters in the first and second slab regions are the same, and then the input and output distances are equal ($x_1 = x$).
- The variation of the focal position x with respect to wavelength λ, for the fixed input light position x_1, can be found by differentiating 6.44 with respect to λ as:

$$\frac{\Delta x}{\Delta \lambda} = -\frac{N_g f \Delta L}{N_s d \lambda_0} \qquad (6.48)$$

where Ns is the effective index in the slab region, and N_g is the group index related to the effective index N_c of the array waveguides, defined as $N_g = N_c - \lambda dN_c/d\lambda$.

Operation of the AWG

- Similarly, the variation of the input side position x_1 with respect to wavelength λ for the fixed light out position x is given by:

$$\frac{\Delta x_1}{\Delta \lambda} = \frac{N_g f_1 \Delta L}{N_s d_1 \lambda_0} \qquad (6.49)$$

- The input and output waveguide spacings are $|\Delta x_1| = D_1$ and $|\Delta x| = D$ respectively when $\Delta\lambda$ is the channel spacing.
- By inserting these relations into 6.48 and 6.49, the wavelength spacing in the output slab can be found for a fixed light input position x_1:

$$\Delta\lambda_{out} = \frac{N_s d D \lambda_0}{N_g f \Delta L} \qquad (6.50)$$

Operation of the AWG

- and similarly the wavelength spacing at the input, for the fixed light output position *x,* is:

$$\Delta\lambda_{\text{in}} = \frac{N_s d_1 D_1 \lambda_0}{N_g f_1 \Delta L}$$

- When the waveguide parameters in the first and second slab regions are the same, then the channel spacings are the same (= $\Delta\lambda$).
- The path length difference, ΔL, can be found from 6.50 as

$$\Delta L = \frac{N_s d D \lambda_0}{N_g f \Delta\lambda}$$

Operation of the AWG

- The theory of the optimum shape of the arrayed waveguides will not be discussed here, but there are a number of restrictive conditions for several waveguide parameters.
- The minimum bend radius should be obviously be larger than the known minimum bending radius of the rib waveguides used in the design, as discussed earlier in this chapter.
- The straight lengths should be larger than the length required to taper the waveguide array elements into the slab in a lossless manner, and the minimum array waveguide separation at the centre should be larger than the minimum coupling width so that the ribs do not interact in the manner of a waveguide-to-waveguide coupler.
- Although there are many design possibilities for a given AWG specification, the best design is the one in which the array waveguide lengths are as short as possible so as to minimize phase errors.

Operation of the AWG

- The spatial separation of the m^{th} and $(m + 1)^{\text{th}}$ focused beams for the same wavelength is given from 6.43 as:

$$X_{\text{FSR}} = x_m - x_{m-1} = \lambda_0 f / N_s d$$

- X_{FSR} is called the free spatial range of the A WG, in the same way that different diffraction orders of other gratings and interferometers are used to specify the free spectral range of those devices.
- The number of wavelength channels, N_{ch}, that can be utilized is found by dividing X_{FSR} by the output waveguide separation D as:

$$N_{\text{ch}} = \frac{X_{\text{FSR}}}{D} = \frac{\lambda_0 f}{N_s d D}$$

Operation of the AWG

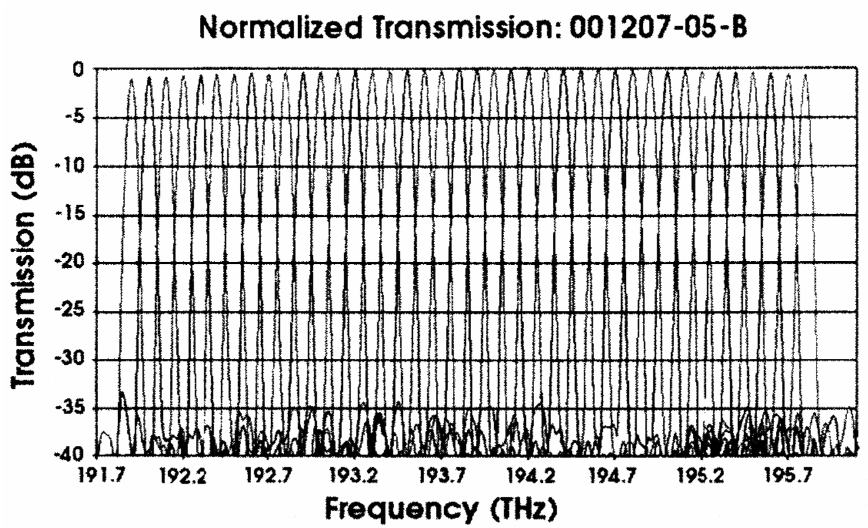

Figure 6.33 40-channel A WG frequency response.

Operation of the AWG

- The frequency response of a typical 40-channel AWG is shown in Figure 6.33.
- The crosstalk is less than 30 dB.
- Devices have been manu-factured with up to 128 ports with channel spacing of 12.5 GHz.
- An AWG provides a fixed routing of an optical signal from a given input port to a given output port based on the wavelength of the signal.
- Signals at different wavelengths coming into an input port will each be routed to a different output port.
- Also, different signals using the same wavelength can be input simultaneously to different input ports and still not interfere with each other at the output ports.
- Compared to a passive star coupler in which the given wavelength may only be used on a single input port, the AWG with *N* input and *N* output ports is capable of routing a maximum of N^2 connections, as opposed to a maximum of *N* connections in the passive star coupler. This is shown schematically in Figure 6.34.

Operation of the AWG

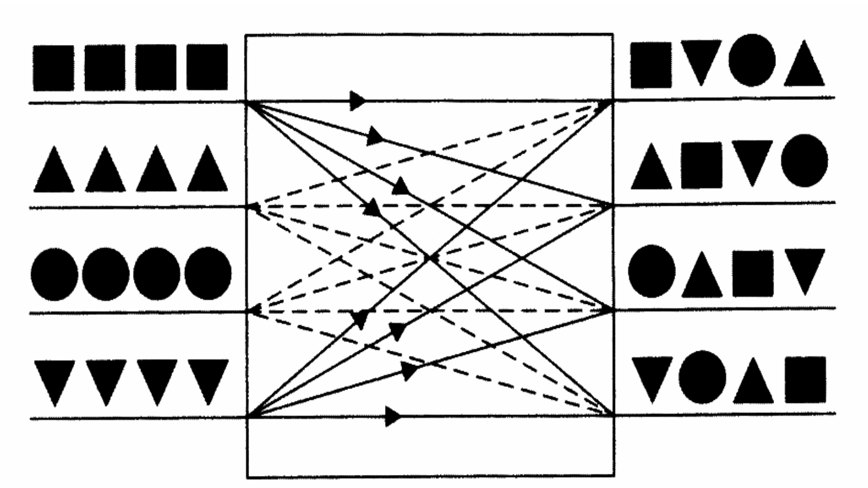

Figure 6.34 Arrayed waveguide grating router (functional schematic).

Operation of the AWG

- However, if there are *N* input and *N* output ports and *n* possible wavelengths on each input port, because of the cyclic nature of the distribution of the wavelengths between the input ports and output ports, a fixed routing structure is obtained.
- This means that different orders of diffraction are effectively being used at the same time in the AWG.
- This causes difficulties because the outer ports suffer higher losses than the central ports.
- The main disadvantage of the AWG is that it is a device with a fixed routing matrix, so it cannot be reconfigured.

6.6 WAVEGUIDE COUPLERS FOR SMALL-DIMENSION WAVEGUIDES

WAVEGUIDE COUPLERS FOR SMALL-DIMENSION WAVEGUIDES

- In Chapter 4 we noted the trend to smaller waveguide dimensions, and the associated difficulty of coupling to small waveguides.
- In this section we will study two possible solutions to this problem in the form of two distinct devices.
- These are the *three-dimensional taper* and the *dual grating-assisted directional coupler* (DGADC).
- Examples of Three-dimensional taper has been published by Confluent Photonics [17], and by Prather et al. [18], as shown in Figure 6.35.

WAVEGUIDE COUPLERS FOR SMALL-DIMENSION WAVEGUIDES

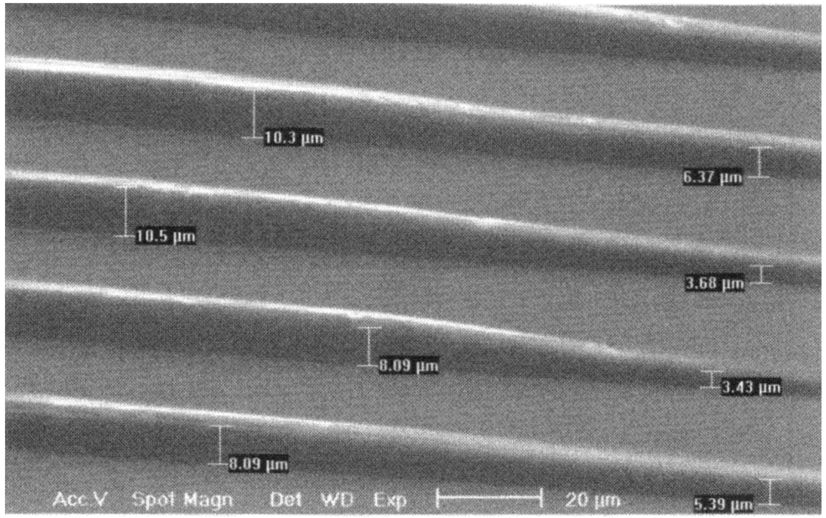

Figure 6.35 An example of vertical tapers in silicon, to act as couplers to small waveguides.

WAVEGUIDE COUPLERS FOR SMALL-DIMENSION WAVEGUIDES

- Authors typically quote losses of between 0.7 dB and 1 dB per interface for three-dimensional tapers, although this figure rises sharply for cross-sectional dimensions of the waveguide smaller than approximately 2μm.
- An alternative technique based upon grating was introduced by Butler et al. [19], who proposed a grating-assisted directional coupler.
- A schematic of a similar type of device is shown in Figure 6.36.

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- The idea is that light can be efficiently coupled from an optical fiber to the large surface waveguide, waveguide *b,* and then the grating is used to couple light to the thin silicon waveguide, waveguide *a.*
- Unfortunately, waveguides *a* and *b* need to be so different in both dimensions and refractive index that only low-efficiency coupling results.
- In the work of Butler et al. [19], the maximum coupling efficiency, for TE polarization, was only 40 % for optimized waveguide and grating parameters.
- Furthermore, for a change in the grating period of just 0.3 nm, the coupling efficiency dropped by almost 50 %, making the fabrication of this grating-assisted directional coupler extremely difficult to realize, and impractical for commercial applications.

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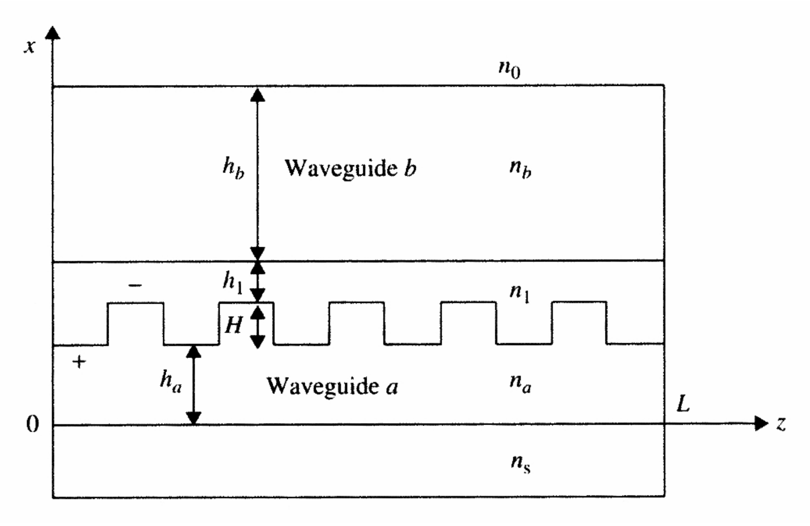

Figure 6.36 Grating-assisted directional coupler.

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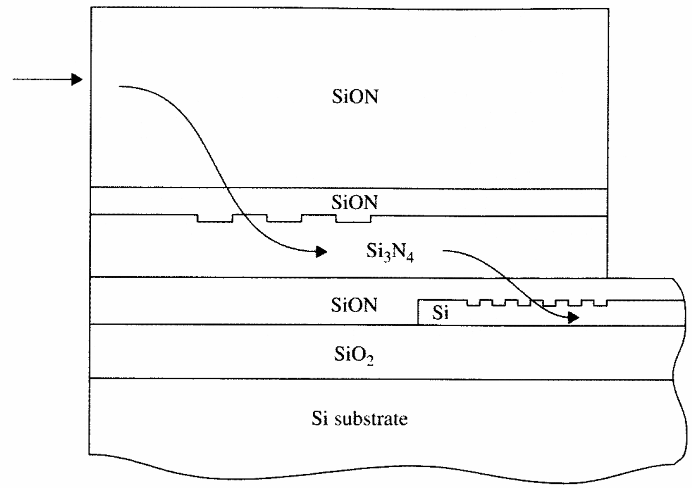

Figure 6.37 Dual grating-assisted directional coupler in SOI

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- In 2003, a new approach based upon grating was proposed by Masanovic et al. [20,21], the dual grating-assisted directional coupler, which consists of two conventional gratings linked by one layer with the value of refractive index that lies between the fiber refractive index and semiconductor refractive index.
- This layer is of crucial importance for achieving high coupling efficiency.
- The device is shown in Figure 6.37.
- The DGAGC is similar to the coupler in Figure 6.35 in that light is coupled from a fiber into a large surface waveguide, and then transferred to a thin silicon waveguide.

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- However, the use of two gratings and an intermediate layer gives sufficient additional flexibility to optimize the coupling process, and to achieve grating dimensions that are relatively straightforward to fabricate.
- The authors demonstrated a theoretical coupling efficiency to a waveguide of only 250 nm in thickness, of up to 96 %, corresponding to a coupling loss of less than 0.18 dB.
- However, at the time of writing this text, no satisfactory coupler was experimentally available for coupling with high efficiency to waveguide of less than about 2μm in cross-sectional dimensions, although those devices discussed above show significant potential.
- This is clearly a challenge for silicon photonics in the next few years.