# Silicon Photonics
# 矽光子學
# Other Issues (B)

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# Outline

- **7.4 BIREFRINGENCE**
- **7.5 THE EFFECT OF STRESS**
- **7.6 DISCUSSION**
- **7.7 CONCLUSION**

# BIREFRINGENCE

- The term 'waveguide birefringence' has emerged from the fiber and integrated optics fields.
- It is used to describe the difference between either propagation constants or effective indices of the two polarization modes of the waveguides in question.
- The term is used indiscriminately to all waveguides regardless of the materials from which they are fabricated, or the origin of the difference in effective indices.
- According to the definition of 'birefringence' this is an inaccurate use of the term, because birefringence strictly means the inherent 'double refraction' of light due to the crystal structure of a given material.

# BIREFRINGENCE

- Double refraction means that if unpolarized light is incident upon a birefringent crystal, two refracted beams rather than one emerge.
- If the angles of incidence and refraction are considered, only one of the refracted beams obeys Snell's law, as described in Chapters 1 and 2.
- This is termed the 'ordinary ray' or 'o' ray.
- The second ray is termed the 'extraordinary ray', or the 'e' ray.
- The degree of refraction of the extraordinary ray is determined by the degree of birefringence of the crystal in question.
- Thus crystals that exhibit double refraction are anisotropic, and all crystals except those belonging to the cubic system are anisotropic to some extent.

# BIREFRINGENCE

- Silicon, however, is a cubic crystal, and hence is isotropic, and as such is not inherently birefringent.
- In practice this means that the refractive index of silicon is constant regardless of the direction of propagation within the crystal.
- Of course this is not true of an anisotropic crystal such as lithium niobate, also used extensively for integrated optical circuits.
- In lithium niobate the ordinary and extraordinary refractive indices are $n_o$ = 2.29 and $n_e$ = 2.21 [6].
- If light is propagating along a principal crystal axis of lithium niobate, the refractive index will be either $n_o$ or $n_e$, depending on the polarization of the light, unless the light is propagating along the optical axis, in which case both the e-ray and the o-ray will see a refractive index of $n_o$.

# BIREFRINGENCE

- If, however, light is propagating at an arbitrary angle to the principal axes, the ordinary ray will see a refractive index of $n_o$, but the extraordinary ray will see a refractive index somewhere between $n_o$ and $n_e$ which is determined by the direction within the crystal (see for example [5]).
- Thus the apparent birefringence within a lithium niobate waveguide depends not only on the geometry of the waveguide itself, but also on the direction of the waveguide within the crystal structure.

# BIREFRINGENCE

- This situation is complicated further in lithium niobate by the fact that it is a crystal that exhibits a large electro-optic effect.
- The refractive index change with applied electric field (as with all electro-optic crystals) is also dependent on the orientation of the field with respect to the crystal.
- Hence, the crystal orientation is important not only to the birefringence of the crystal, but also to the operation of devices such as electro-optic modulators.
- Of course it is the very fact that the crystal structure is not cubic that results in the electro-optic effect being present, so the two effects are obviously related. The converse is true for silicon in which the linear electro-optic effect is absent owing to the symmetrical nature of the crystal structure.

## Birefringence in Planar Silicon Waveguides

- Because silicon is optically isotropic, the apparent waveguide birefrin-gence is due solely to the different propagation constants resulting from the solution of slightly different eigenvalue equations (ignoring parasitic effects such as stress, to be discussed later).
- Whilst this makes silicon less complex than anisotropic materials, this apparent birefringence can still have serious consequences for devices based on planar waveguides in which relative phase between modes is important.
- To consider this further let us evaluate the propagation constants for a planar waveguide of the form discussed in section 7.1.
- Let the waveguide thickness be 1 $\mu$m, and the exciting wavelength be 1.3 $\mu$m.
- If we solve the eigenvalue equations (7.3 and 7.4) for such a waveguide, it is clear that the waveguide will support five TE modes and five TM modes.

## Birefringence in Planar Silicon Waveguides

- The propagation constants of each of these modes is listed in Table 7.6.
- Recall from Chapter 2 that the phase shift with propagation distance can be evaluated as the product of the propagation constant, $\beta$, and the physical length, $L$.
- Without specifying a device, let us assume a propagation length of 1 mm, a typical length for some devices and waveguides.
- The $\beta L$ product is also evaluated in Table 7.6.

**Table 7.6** Propagation constants in a 1 μm planar silicon waveguide

| Mode number, $m$ | Propagation constant (TE modes) | Propagation constant (TM modes) | Phase change, $\beta L$ | |
|---|---|---|---|---|
| | | | TE | TM |
| 0 | 16.687 $\mu m^{-1}$ | 16.636 $\mu m^{-1}$ | 5311.6$\pi$ | 5295.4$\pi$ |
| 1 | 15.983 $\mu m^{-1}$ | 15.769 $\mu m^{-1}$ | 5087.5$\pi$ | 5019.4$\pi$ |
| 2 | 14.751 $\mu m^{-1}$ | 14.227 $\mu m^{-1}$ | 4695.4$\pi$ | 4528.6$\pi$ |
| 3 | 12.880 $\mu m^{-1}$ | 11.822 $\mu m^{-1}$ | 4099.8$\pi$ | 3763.4$\pi$ |
| 4 | 10.150 $\mu m^{-1}$ | 8.506 $\mu m^{-1}$ | 3230.8$\pi$ | 2707.5$\pi$ |

## Birefringence in Planar Silicon Waveguides

- We can immediately see from Table 7.6 that the phase change over 1 mm of each of the modes varies considerably, both with mode number and polarization.
- Consequently, any device that relies on particular phase relationships over the length of the device will be seriously compromised by a change from single- to multi-mode behavior.
- Similarly, any device which relies on negligible waveguide birefringence over such a propaga-tion distance will be compromised.
- Consider a simple example in which the device is designed to be a fixed length, but fabrication tolerances result in a device $\delta L$ = 0.5 $\mu$m longer than designed.

## Birefringence in Planar Silicon Waveguides

- The additional phase shift difference between the fundamental TE and first-order TE modes due to the extra length will be:

$$\delta\phi = (\beta_{TE0} - \beta_{TE1})\delta L = (16.687 - 15.983) \times 0.5$$
$$= 0.352 \text{ radians} \equiv 20.2^\circ \qquad (7.8a)$$

- Similarly the phase difference between fundamental TE and TM modes can be evaluated as:

$$\delta\phi = (\beta_{TE0} - \beta_{TM0})\delta L = (16.687 - 16.636) \times 0.5 = 0.0255 \text{ radians}$$
$$\equiv 1.46^\circ \qquad (7.8b)$$

- Of course this means that the TE and TM modes will experience a phase difference of 1.46° for every 0.5 $\mu$m of waveguide length.

## Birefringence in Silicon Rib Waveguides

- In common with the planar waveguides, the waveguide birefringence of rib waveguides can be studied by comparing the propagation constants of the modes of the rib waveguides.
- This is equivalent to studying the effective index difference of modes of the rib waveguides since, from Chapter 4, we know that:

$$\beta = k_0 N_{wg} \qquad (7.9)$$

where $N_{wg}$ is the effective index of the propagating mode.

- In order to compare the effect of birefringence on a waveguide device, let us consider the effect of birefringence on a Mach-Zehnder interferometer.
- A schematic of the interferometer is shown in Figure 7.10.

## Birefringence in Silicon Rib Waveguides

- The polarization dependence of the Mach-Zehnder will manifest itself in the difference in propagation constants of the waveguides, and the corresponding difference in phase delay in the interferometer. In order to demonstrate this effect in more detail, let us consider a specific example.

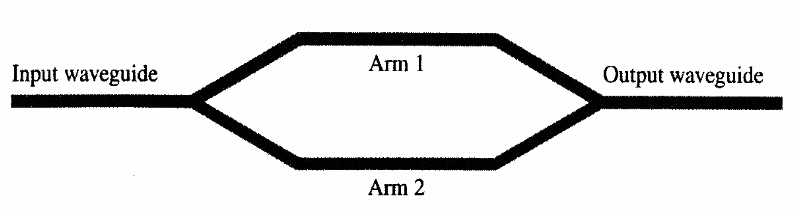


Figure 7.10 Schematic of a waveguide Mach-Zehnder interferometer

## *Example of a Mach-Zehnder Interferometer*

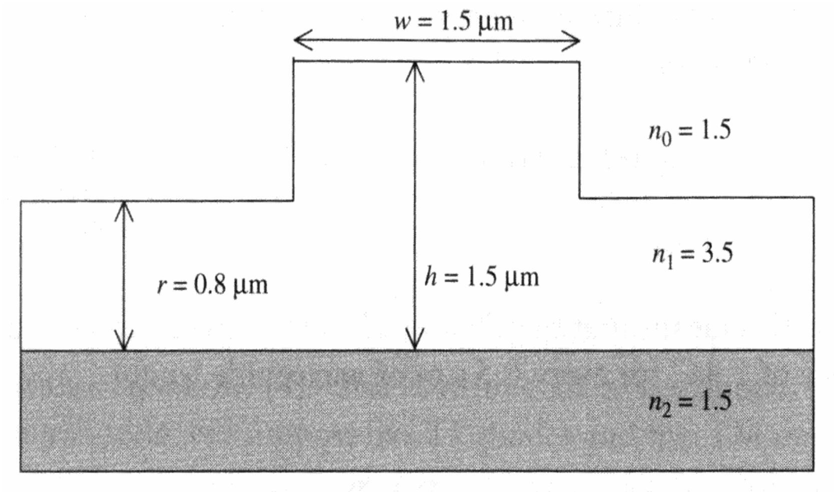


Figure 7.11 Rib waveguide parameters used in the Mach-Zehnder interferometer example

## *Example of a Mach-Zehnder Interferometer*

- Let the rib waveguides of the Mach-Zehnder have the dimensions shown in Figure 7.11. We can then evaluate the effective indices of the fundamental TE and TM modes. The values of the effective indices are
  - $N_{wg}$(TE) = 3.4651 and $N_{wg}$(TM) = 3.4607.
- This corresponds to propagation constants of , $\beta$ *(TE)* = 16.748 $\mu$m$^{-1}$ and $\beta$ *(TM)* = 16.726 $\mu$m$^{-1}$
- If we assume a wavelength of operation of $\lambda$ = 1.3 $\mu$m, we can plot the transfer function of the interferometer with increasing path length dif-ference, $\Delta L$, between the two arms of the interferometer.

## *Example of a Mach-Zehnder Interferometer*

- When the path length difference is small, the polarization dependence will be less noticeable, because the phase shift, $\beta \Delta L$, for the TE and TM modes will be similar if $\Delta L$ is small.
- However, as the path length difference is increased, then the phase difference at the output between the two arms for the TE and TM modes will also increase.
- For the propagation constants evaluated in the example above, the transfer function of the interferometer shows significant polarization dependence when $\Delta L$ reaches a few tens of microns.
- To demonstrate this, Figure 7.12 shows the two transfer functions when the path length difference is of the order of 100 $\mu$m.

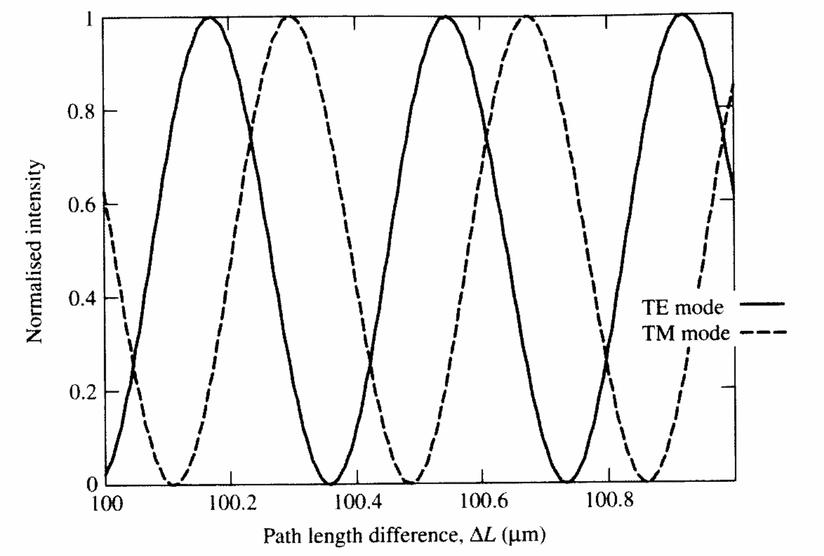


Figure 7.12 Interferometer transfer function for TE and TM modes

## *Example of a Mach-Zehnder Interferometer*

- If we consider an operating wavelength of 1.3 $\mu$m, the refractive index change with injected carriers was described in Chapter 4, reproduced below as equation 7.10:

$$\Delta n = \Delta n_e + \Delta n_h = -[6.2 \times 10^{-22} \Delta N_e + 6.0 \times 10^{-18} (\Delta N_h)^{0.8}] \quad (7.10)$$

- If we assume carrier injection levels of $\Delta N_e = \Delta N_h = 1 \times 10^{18}$ cm$^{-3}$, then:

$$\Delta n = -2.13 \times 10^{-3} \quad (7.11)$$

## *Example of a Mach-Zehnder Interferometer*

- If the interferometer is designed to be nominally at a null for the TE mode (at $\Delta L$ = 100.36 $\mu$m), if a TM mode is also present, the null will be seriously compromised by the TM mode being almost 75 % of its peak value.
- Of course the relative intensity of the TE/TM interference patterns will also be affected by the amount of optical power in each of the modes, but an equal split would not be an unreasonable assumption if the device is fed by a standard communications fiber, providing randomly polarized light.
- We can take this straightforward analysis one stage further by considering what would happen in a waveguide modulator based around a Mach-Zehnder interferometer.
- We saw in Chapters 4 and 6 the way in which injection of free carriers affects the refractive index of silicon, and cab be used to fabricate an optical modulator.

## *Example of a Mach-Zehnder Interferometer*

- By applying this change in refractive index to the rib waveguides of the Mach-Zehnder above we can consider the relative change in propagation constant of the fundamental mode for TE and TM polarizations.
- The TE mode propagation constant changes from $\beta$ (TE) = 16.748 $\mu$m$^{-1}$ to $\beta$(TE) = 16.737 $\mu$m$^{-1}$.
- Similarly the TM mode propagation constant changes from $\beta$ (TM) = 16.726 $\mu$m$^{-1}$ to $\beta$(TM) = 16.716 $\mu$m$^{-1}$.
- Thus, whilst there is nominally no inherent polarization dependence of carrier injection, there is a small secondary effect that may be significant over very long devices.

## Example of a Mach-Zehnder Interferometer

- For example, a carrier injection modulator in silicon may typically be 1000 $\mu$m in length.
- The difference in phase shift, $\Delta\phi$, over this length between the modulated and the un modulated propagation constants for the TE mode is approximately $\Delta\phi$(TE) = 11°.
- For the TM mode, approximately $\Delta\phi$(TM) = 10°.
- Clearly this small difference is insignificant when compared to the absolute polarization dependence, over this sort of device length; but if the propagating signals were to pass through a series of cascaded Mach-Zehnder interferometers (in an add-drop filter for example), the effect could become much more significant.

## Examples of Birefringence in Rib Waveguides

- However, before we produce results as an example, let us first consider the model we use to carry out such a task.
- So far the effective index model has served us well.
- However, this model can be inaccurate in circumstances associated with high index difference, or dimensions of the order of a wavelength.
- This becomes particularly important when considering modes with similar propagation constants (and hence similar effective index). This is the case when considering similar order modes of different polarizations, so care must be taken when using the effective index model.
- To demonstrate this let us evaluate the effective index difference for the fundamental modes of a waveguide, one of TE polarization, and the other TM.

## Examples of Birefringence in Rib Waveguides

- So far in the discussion of rib waveguides the degree of birefringence for different waveguides has not been explicitly investigated.
- Following the argument associated with the effective index method, we can think of the vertical and horizontal confinement of an optical mode to be subject to opposing polarization constraints.
- That is to say, the polarization of the nominally TE mode in a rib is subject to 'TE-type' confinement in the vertical sense, and 'TM-like' confinement in the horizontal sense. The converse is true for the TM modes.
- Therefore we can expect the propagation constants of the TE and TM modes to be affected differently to changes in waveguide geometry such as a change in rib width etc.
- Consequently, it is informative to consider the degree of waveguide birefringence for a given rib waveguide height, and how it varies with waveguide width or etch depth.

## Examples of Birefringence in Rib Waveguides

- Consider a large waveguide, with a waveguide height of (say) 5 $\mu$m.
- If we set the vertical parameter *r* (see Figure 7.11) to be 3, 2 or 1 $\mu$m (etch depths of 2, 3 or 4 $\mu$m), we can look at the variation in effective index with varying waveguide width and etch depth.
- This is plotted in Figure 7.13, using the effective index method to produce the graph. The results are useful in general terms.
- For example, it can be seen that at larger widths, the etch depth has little effect on the modal birefringence.

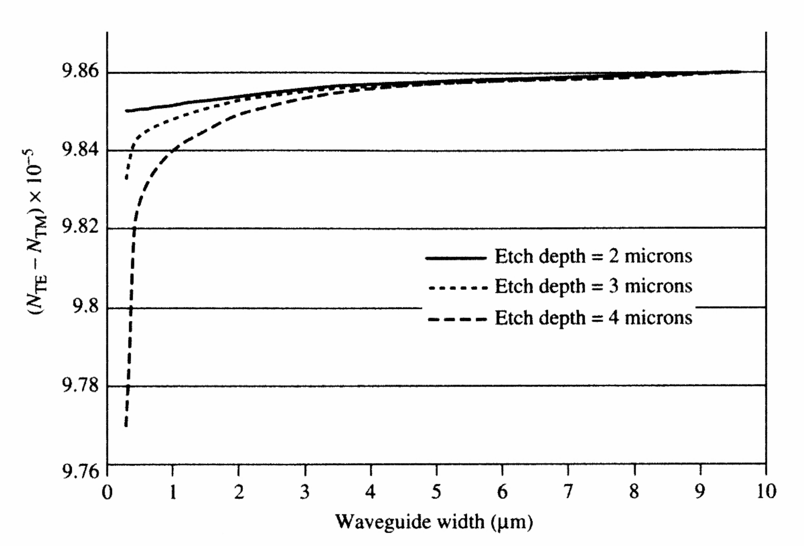


Figure 7.13 Variation of fundamental-mode effective index difference of a 5 $\mu$m waveguide (height) for various etch depths and waveguide widths (effective index method)

## *Examples of Birefringence in Rib Waveguides*

- If we now produce the same graph using a commercial simulator, using the beam propagation method in the simulator, with semi-vectorial capability.
- Figure 7.14 is the result.
- There is a striking difference between the graphs of Figure 7.13 and 7.14.
- Not only are the graph shapes different but in Figure 7.14 two of the curves cross the ‘zero birefringence’ axis (i.e. $N_{TE}$ - $N_{TM}$ = 0).
- This indicates that using deeper etch depths makes it is possible to produce birefringence-free waveguides for some of the waveguide geometries and dimensions of Figure 7.14.
- Figure 7.14 also reflects what we expect to occur in a practical device.

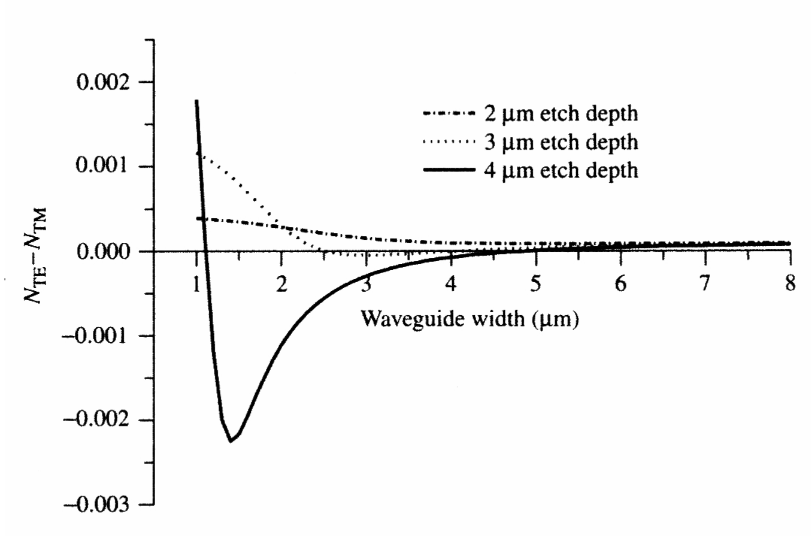


Figure 7.14 Variation of fundamental-mode effective index difference of a 5 $\mu$m waveguide (height) for various etch depths and waveguide widths (beam propaga-tion method)

## *Examples of Birefringence in Rib Waveguides*

- For very large waveguide widths, the device will be 'slab-like', and hence the TE effective index will be higher.
- As the width is reduced the 'TM-like' confinement will compete with 'TE-like' confinement in an 'intermediate stage'.
- However, when the waveguide width becomes very small, most of the power will be confined to the underlying slab region, and the mode will again exhibit slab-like behavior and hence higher TE effective indices than TM.
- The question of whether the curve actually crosses the 'zero birefringence' axis is a function of the relative values of the TE and TM effective indices in the intermediate stage, which is clearly affected by the etch depth.

## *Examples of Birefringence in Rib Waveguides*

- Now let us consider similar curves for a much smaller waveguide, with say a waveguide height of only 1 $\mu$m.
- Evaluating the difference in effective index for the fundamental modes in this case results in Figure 7.15. In this case two etch depths are considered, of *e* = 0.5 and 0.75 $\mu$m.
- We see similar trends in both the smaller and larger waveguides, but notice that for the smaller waveguides of Figure 7.15, the zero birefringence axis is crossed only for the deeper of our two etch depths, which is a substantial proportion of the overall waveguide height.

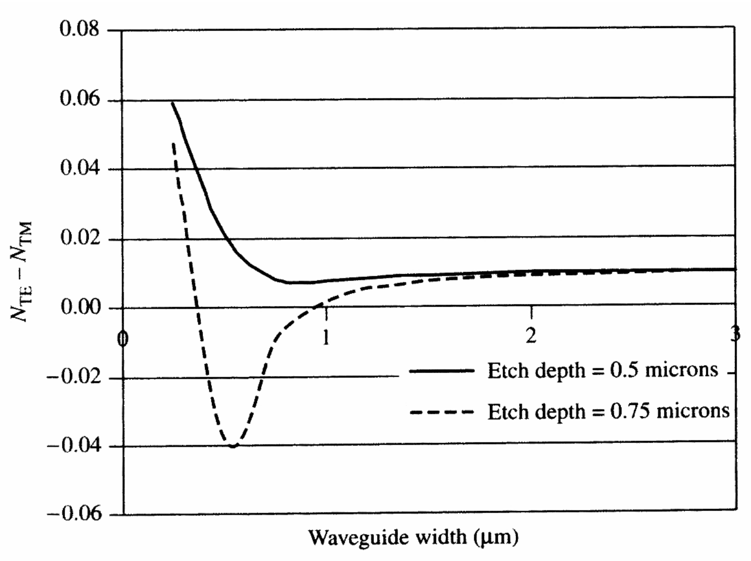


Figure 7.15 Variation of fundamental-mode effective index difference of a 1 $\mu$m waveguide (height) for variation in etch depth and waveguide width (beam propagation method)

## *Examples of Birefringence in Rib Waveguides*

- Thus it is probably easier to fabricate a large rib waveguide that is polarization-independent than a small one.
- It is also worth noting that the difference in effective indices of the wider of the larger ribs (to the right-hand side of Figure 7.14) saturates at a level of less than $10^{-4}$.
- This is very much smaller than the equivalent value in Figure 7.15, which is approximately $10^{-2}$, two orders of magnitude larger. Hence larger ribs are inherently less birefringent than smaller ones.
- This is because the relative effect of the waveguide boundary is enhanced in smaller waveguides.

# 7.5 THE EFFECT OF STRESS

# Effect of Stress

- It is well known that mechanical stress in a material can induce changes in the optical properties of that material.
- The existence of stress within a silicon wafer can turn a nominally isotropic material into an optically anisotropic one.
- This is known as *stress birefringence,* or *the photo-elastic effect.*
- The semiconductor processing laboratory, together with device packaging, offer numerous opportunities of introducing stress to semiconductor devices and wafers.
- For optical waveguides this means that the potential exists for stress-induced changes in refractive index of the waveguiding layer.
- For example, the apparently simple act of depositing a protective oxide layer, or a metallic contact, may introduce stress into a silicon-based optical system.

# Effect of Stress

- This is particularly problematic when the resulting strain field is directional, because this will result in directional changes in the optical properties of the waveguide.
- This commonly translates to polarization-dependent changes in propagation characteristics and/or losses. Of course, these 'accidental' stress fields will typically be of arbitrary direction, but the near planar surface of a silicon circuit means that it is relatively easy to accidentally introduce a directional stress field.
- Rather than attempt to quantify some arbitrary directional change in polarization characteristics of a silicon waveguide, it is perhaps instruc-tive to consider an application where stress in an optical system is made a virtue.
- Such a case is the high-birefringence optical fiber (also called the 'polarization maintaining fiber').

# Effect of Stress

- In such fibers, a directional stress field is deliberately introduced to ensure that orthogonal polarization modes propagate with significantly different propagation constants.
- That is to say the fiber is birefringent.
- We have seen in Chapter 2 that a circularly symmetric optical fiber results in orthogonal polarizations propagating with essentially the same propagation constant.
- This means power transfers between these modes, resulting in an output wave with a random state of polarization.
- If the propagation constants of orthogonal modes are sufficiently different, little or no such exchange of power results, and hence the state of polarization is maintained.

# High-Birefringence Fiber

- Figure 7.16 shows three examples of polarization-maintaining fibers fabricated with stress-generating inclusions.
- The shaded areas represent doped silica regions that have large thermal expansion coefficients, which are inserted to introduce directional stress w

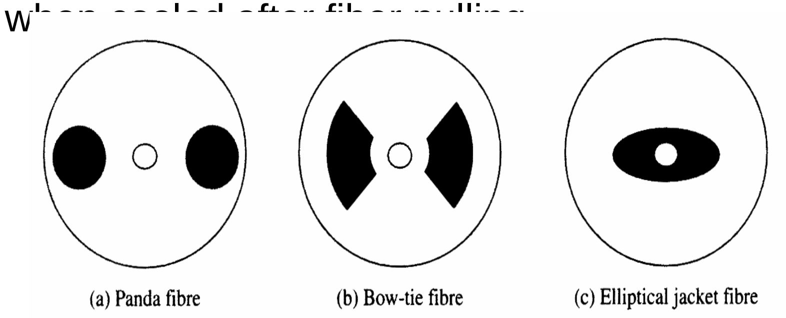


Figure 7.16 Three types of high-birefringence fiber formed by stress-inducing inclusions

# Effect of Stress

- Typically a tensile force is generated in one cross-sectional direction, and a compressive force in the orthogonal direction.
- This changes the refractive indices by the photoelastic effect.
- For a polarization-maintaining fiber, the modal birefringence, *B,* is usually quantified in terms of the normalized difference of the orthogonal propagation constants:

$$B = \frac{\beta_x - \beta_y}{k_0} \qquad (7.12)$$

- Typical modal birefringence for a polarization-maintaining fiber is of the order of $B = 5 \times 10^{-4}$

# DISCUSSION

- It is clear from the foregoing sections that the response to light of differing polarization can be vital to the operation of a silicon optical circuit. In particular when the circuit is fed by a standard communications optical fiber, resulting in excitation of the circuit with randomly polarized light, in some applications it is important that the circuit be insensitive to polarization.
- We have seen the effect of polarization in propagation in planar and rib waveguides and in coupling to such waveguides, the effect of multimode waveguides, and the effect on some simple devices.
- Prior to discussing the entire effect of polarization, it is perhaps worth considering one further specific effect on a device, a device that is particularly affected by relative phase, the arrayed waveguide grating (AWG).

# The Effect of Polarization and Multimode Sections on the AWG

- In Chapter 6, the AWG as a wavelength demultiplexer was discussed.
- A series of discrete coherent sources were used to demonstrate that a linearly increasing phase shift across a number of sources allows multi beam interference to result in a focusing effect, and constructive interference at a point.
- This is used to advantage in the AWG, in which the total phase change accumulated as a wave passes through the device is used to allow multi beam interference to occur in an output slab waveguide.
- Consequently, there are two specific effects discussed in this chapter that may compromise the effectiveness of the AWG to successfully allow constructive interference in the output slab; these are (i) the multimode behavior of the input and output slabs, and (ii) the polarization sensitivity of the entire device.

# The Effect of Polarization and Multimode Sections on the AWG

- In both cases the existence of modes with differing propagation constants (either higher-order modes or modes of different polarization) will result in the AWG focusing at a slightly different position in the output slab waveguide of the AWG.
- This appears as an apparent frequency shift in the output of the device, and effectively results in channel crosstalk in the AWG.
- The frequency shift, $\Delta f$, between polarization modes has been conveniently described by Smit and van Dam [7] as:

$$\Delta f \approx f \frac{N_{TE} - N_{TM}}{N_{TE}^{g}} \qquad (7.13)$$

where *f* is the centre wavelength of the A WG, $N_{TE}$ and $N_{TM}$ are the effective indices for the TE and TM polarizations, and $N^{g}_{TE}$ is the group index of the waveguide TE mode.

## *Multimode Behavior of the Input and Output Slabs*

- We have seen in this chapter that different modes of a planar waveguide will propagate with different resulting phase shifts.
- This will result in 'ghosting' in the output slab of the AWG, as each mode has a different focal point in the output slab.
- In effect this is additional crosstalk.
- It should be noted, however, that this is not a phenomenon unique to SOI AWGs, but will occur in all AWGs that employ multimode slab regions within the device.
- The degree of crosstalk will be related to the phase differential between modes, as calculated earlier, but crucially, also to the relative optical power in each of the waveguide modes.

## *Multimode Behavior of the Input and Output Slabs*

- Consequently, even if higher-order modes exist, if power can be prevented from coupling to these modes, or the modes can be made to be lossy, then little ghosting will occur.
- In order to estimate the relative coupling from rib waveguides to the modes of the slab regions, an overlap integral must be performed.
- This has been carried out, for example, by Pearson et al. [8], who showed that for a silicon on insulator AWG based upon a 1.5 $\mu$m silicon layer, coupling to the fundamental mode of the slab is more than two orders of magnitude higher than coupling to higher-order modes.
- This is demonstrated in Figure 7.17. This demonstrates that it is possible to design an AWG such that the multi mode nature of the slab region does not unduly affect the output interference pattern, because higher-order modes of the slab are very poorly excited.

- Consequently the polarization dependence of the AWG is much more likely to be problematic than the modal characteristics.

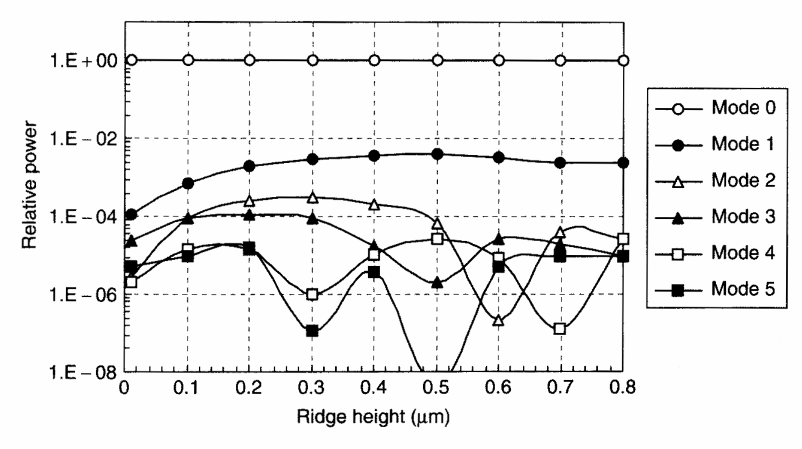


Figure 7.17 Relative power coupling to slab modes from a single-mode input rib.

# *Polarization Sensitivity of the AWG*

- The polarization sensitivity of the AWG arises from two sources, the polarization dependence of the array waveguides, and the polarization dependence of the slab regions.
- Both these effects have been discussed in preceding sections of this chapter, and hence will be discussed only briefly here.
- Firstly we have seen that the array waveguides (rib waveguides) will, in general, be polarization-dependent.
- However, we have also seen that it is possible to design such waveguides to be nominally polarization -independent.
- In practice this design may be compromised somewhat by unwanted strain, although even this could be 'designed out' if consistent effects were present.

# Polarization Sensitivity of the AWG

- We have not, however, considered compensating the polarization dependence of the slab region of the AWG. Cheben et al. [9] studied this problem, producing a partially etched region of both the input and output slabs.
- The aim was to totally neutralize the phase difference between TE and TM modes in the AWG (in both slab and rib regions), by creating a prism-like region in the slabs, thus effectively altering the optical path lengths of the TE and TM modes in the slab regions, to compensate for the relative phase differences.
- This is an extremely elegant solution to the problem, producing impressive results.
- A graph relating etch depth of the compensating region and polarization dispersion for both theoretical and experimental results is shown in Figure 7.18.

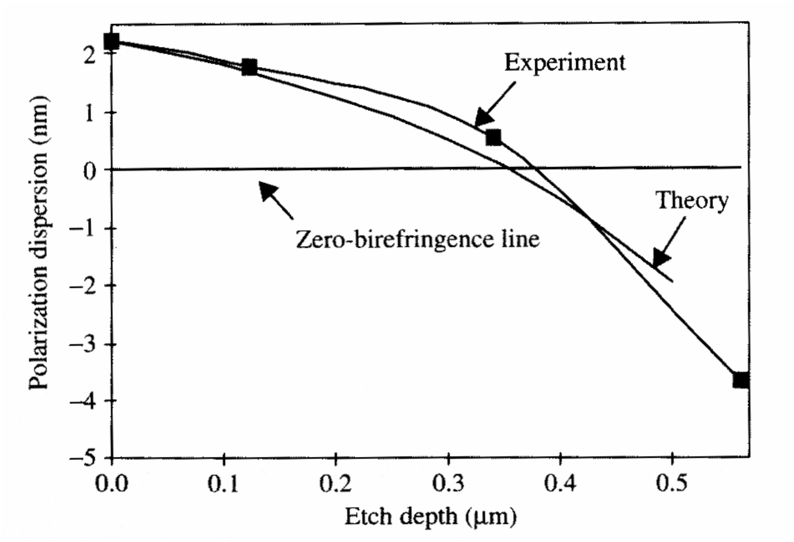


Figure 7.18 Dispersion of the compensator with etch depth.

# Polarization Sensitivity of the AWG

- A variety of other approaches to polarization compensation have also been reported. In 1993, Zirngibl et al. [10], designed an InP AWG with a free spectral range to be the same as the separation of the TE and TM mode patterns in the output slab.
- This means that the grating order of the AWG for the TE mode is exactly one order higher than for the TM.
- Thus the two patterns are coincident in the output slab. The disadvantage of this method is that the spectral width of the device is limited by the polarization dispersion, resulting in a relatively narrowband device.

# Polarization Sensitivity of the AWG

- A more elegant solution was demonstrated by Takahashi et al. [11], who inserted a quartz ) $\lambda/2$ plate into the mid point of their AWG.
- The halfwave plate converts TE polarized light to TM, and vice versa.
- Hence light entering the AWG as TE polarized light propagates through half the device as TE polarization, and half the device as TM polarization.
- Similarly light entering as TM polarization propagates the second half of the device as TE polarization.
- Consequently exactly the same phase change is experienced by the TE and TM modes.
- Of course the assump-tion is that the halfwave plate can be placed exactly at the mid point of the AWG.
- This approach is suitable only if a halfwave plate can be used that is small compared to the divergence of the waveguides, since the 'gap' containing the halfwave plate must be crossed without too much loss.

# Polarization Sensitivity of the AWG

- In silicon waveguides the numerical aperture is large owing to the large refractive index contrast, and hence this approach is problematic.
- A method similar to that of Cheben et al. [9] (above) was demonstrated by Zirngibl et al. [12].
- In this case the compensating region was placed in the waveguide array, rather than in the slabs.
- A region of waveguide is introduced into each array waveguide, with a different birefringence from that of the main part of the waveguide.
- Thus the phase difference, $\Delta\phi$ between adjacent waveguides is given by:

$$\Delta\phi = k_0[N_1\Delta L + \delta L(N_1 - N_2)] \tag{7.14}$$

where $\Delta L$ is the length difference between adjacent waveguides, $\delta L$ is the additional length of compensating waveguide, $N_1$ is the effective index of the original waveguide, and $N_2$ is the effective index of the compensating section of waveguide.

# Polarization Sensitivity of the AWG

- If $\Delta N_1$ and $\Delta N_2$ are the differences between the TE and TM values of $N_1$ and $N_2$, the condition for $\Delta\phi = 0$ is found to be:

$$\frac{\delta L}{\Delta L} = \frac{1}{\left(\frac{\Delta N_1}{\Delta N_2} - 1\right)} \tag{7.15}$$

- Hence the entire waveguide array can be made polarization-independent by inserting compensating sections in the array waveguides with increasing multiples of length $\delta L$.
- One other compensation technique reported in the literature is worth mentioning.
- This is the addition of a polarizing splitter at the input to the AWG [7].

# Polarization Sensitivity of the AWG

- This is of course a standard technique for eliminating birefringence, but in most devices it results in duplication of the circuit in question.
- In an AWG, the situation is simplified, because rather than duplicating the entire AWG, it is sufficient simply to use different input waveguides for the TE and TM modes.
- If the input separation is chosen to be equal to the output shift between the polarizations, then the TE and TM outputs will be coincident in the output slab.
- Of course this configuration is suitable only if the AWG use is to be limited to the demultiplexing function.
- Applications such as N x N routing, which use multiple inputs, are obviously excluded.

# The Effect of PDL on Other Devices

- The preceding sections have concentrated the discussion of POL on the AWG, although we have seen that the diversity of effects described under the global term of POL will affect different devices in different ways.
- The effect on the AWG is dominated by considerations of relative phase.
- This will also be true of any interferometric device.
- However, any loss-limited device will be affected more by the relative loss of the TE and TM polarizations.
- For example, a receiver working close to its sensitivity limit will be differentially affected by the loss of the TE and TM modes.

## The Effect of PDL on Other Devices

- Consequently, issues such as surface scattering, and the associated polarization-dependent loss, are important in this situation.
- Similarly, circuits with waveguides with a significant amount of bending may be differentially affected by the different bending loss of the waveguides. Alternatively, evanescent-based devices such as couplers will be affected by the different degrees of confinement of the two polarizations.
- Hence it is clear that the device-specific effects of polarization must be considered when attempting to evaluate the overall impact of polarization on any given device.

# 7.7 CONCLUSION

## CONCLUSION

- This chapter has discussed the effect on devices of different responses to light polarized in the TE or TM directions.
- In particular the effect of waveguide dimensions, surface scattering, polarization-dependent coupling loss, waveguide birefringence, and phase compensation techniques have been discussed and evaluated.
- Occasionally a specific device has been used to demonstrate or quantify the effects of polarization.
- It is clear from the details contained within this chapter that polarization of the incoming signal can have a dramatic impact upon the performance of a given optical circuit or device, particularly when that device is sensitive to variations in phase.
- The overriding conclusion must be that, in order to evaluate the effects of polarization, the dominant contributions to the polarization dependence must be identified and quantified.

## CONCLUSION

- It is also clear from the foregoing that much can be done to combat the effects of polarization in silicon-on-insulator photonics. Indeed, we have demonstrated that, in principle, many of the effects of polarization can be eliminated entirely.
- However, it is also clear that minimizing the effects of polarization of one parameter may increase the effects of another.
- For example, if birefringence is removed by waveguide design, the TE and TM mode shapes will still be different.
- This may increase differential loss via interface scattering.
- Similarly if birefringence is removed in a small waveguide by selecting a specific waveguide geometry, this may result in a multimode waveguide, which could in turn degrade the performance of an interferometer, or result in loss due to leakage from higher-order modes.
- Thus the parameter to be optimized must not be considered in isolation, but as a part of an integrated design process.