Silicon Photonics
矽光子學
Other Issues (A)

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Polarization-dependent Losses

- The response of the optical circuit to the incoming optical signal should ideally be the same regardless of the polarization of that optical beam.
- However, in practice there are a variety of reasons why the response is different.
- This is important because the polarization of the incoming signal may vary, particularly if it originates from a circularly symmetrical optical fiber, which typically provides a signal of random polarization.
- Hence there is not even the opportunity to compensate for a known degree of polarization imbalance, because the relative contributions of each polarization to the total signal may change with time.
- Consequently designers usually aim to minimize any polarization dependence in integrated optical devices.

7.1 THE EFFECT OF WAVEGUIDE THICKNESS

Polarization-dependent Losses

- The net result of different responses to the polarization of the incoming signal usually manifests itself as a different signal loss to each polarization, although the origins of that loss will not usually be limited to an inherent differential loss, but may also be derived from differential phase shifts, different degrees of optical confinement, or differential optical paths lengths within the circuit.
- The difference in loss between the orthogonal polarization components of the signal is usually termed *polarization-dependent loss* (PDL), and it is the issues related to PDL that form the material of this chapter.
- Some of the primary contributions to PDL will be discussed in turn, being pulled together in the discussion and conclusion sections.

THE EFFECT OF WAVEGUIDE THICKNESS

- Let us consider the silicon planar waveguide shown in Figure 7.1.
- We observed in Chapter 2 that the eigenvalue equations for TE and TM polarizations are different.
- This means that the modal solutions to these equations will also be different.

THE EFFECT OF WAVEGUIDE THICKNESS

The eigenvalue equation for TE modes is:

$$[k_0 n_1 h \cos\theta_1 - m\pi] = \tan^{-1}\left[\frac{\sqrt{\sin^2\theta_1 - (n_2/n_1)^2}}{\cos\theta_1}\right] + \tan^{-1}\left[\frac{\sqrt{\sin^2\theta_1 - (n_3/n_1)^2}}{\cos\theta_1}\right] \tag{7.1}$$

- Similarly the eigenvalue equation for TM modes is:

$$[k_0 n_1 h \cos\theta_1 - m\pi] = \tan^{-1}\left[\frac{\sqrt{(n_1/n_2)^2 \sin^2\theta_1 - 1}}{(n_2/n_1)\cos\theta_1}\right] + \tan^{-1}\left[\frac{\sqrt{(n_1/n_3)^2 \sin^2\theta_1 - 1}}{(n_3/n_1)\cos\theta_1}\right] \tag{7.2}$$

THE EFFECT OF WAVEGUIDE THICKNESS

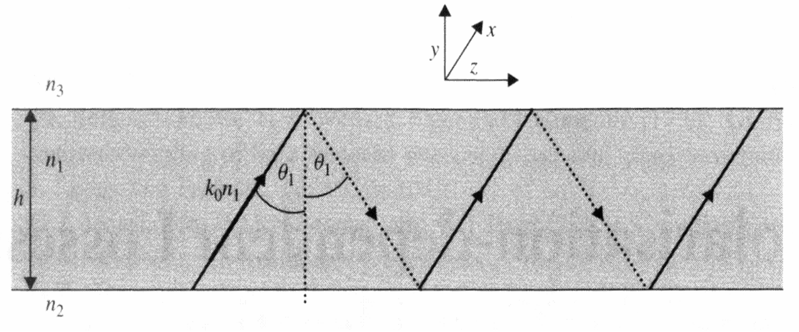

Figure 7.1 Propagation in a planar waveguide

THE EFFECT OF WAVEGUIDE THICKNESS

- To demonstrate the differences between polarization modes, let us consider a series of planar silicon waveguides, and plot the intensity mode profiles of the fundamental mode for both TE and TM polarizations.
- There is relatively little difference between the mode profiles of asymmetric and symmetric waveguides in silicon, so it is convenient to use the symmetric waveguide, particularly since in many practical applications the surface of the silicon wafer will usually have a passivating layer of SiO_2, making the waveguide a symmetrical one.

THE EFFECT OF WAVEGUIDE THICKNESS

- In this case the eigenvalue equations for the TE and TM modes (equations 7.1 and 7.2 above) reduce to:
- For TE polarization:

$$\tan\left[\frac{k_0 n_1 h \cos\theta_1 - m\pi}{2}\right] = \left[\frac{\sqrt{\sin^2\theta_1 - (n_2/n_1)^2}}{\cos\theta_1}\right] \qquad (7.3)$$

- For TM polarization:

$$\tan\left[\frac{k_0 n_1 h \cos\theta_1 - m\pi}{2}\right] = \left[\frac{\sqrt{(n_1/n_2)^2 \sin^2\theta_1 - 1}}{(n_2/n_1)\cos\theta_1}\right] \qquad (7.4)$$

THE EFFECT OF WAVEGUIDE THICKNESS

- If we now determine the fundamental intensity mode profiles for both polarizations, of four symmetrical planar waveguides, we can immediately see the effect of polarization.
- Consider waveguides with the following parameters: $n_1 = 3.5$ (silicon), $n_2 = n_3 = 1.5$ (silicon dioxide), $\lambda_0 = 1.3\ \mu m$.
- If we now determine the fundamental intensity mode profiles for waveguides with heights of 0.3 μm, 1.0 μm, 5 μm and 8 μm, we would expect the confinement of the fundamental modes to increase with increasing height *h.*
- The results are shown in Figures 7.2, 7.3, 7.4 and 7.5.

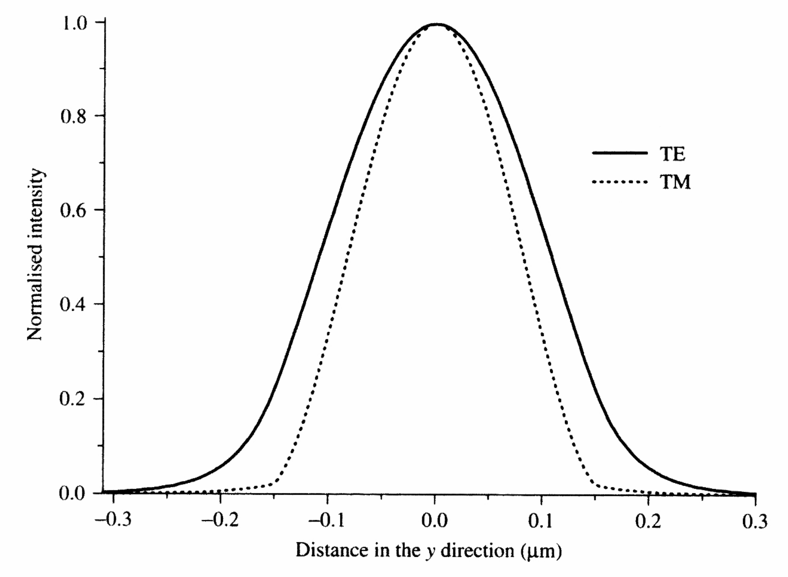

Figure 7.2 TE and TM intensity profiles for a waveguide height of $h = 0.3\ \mu m$

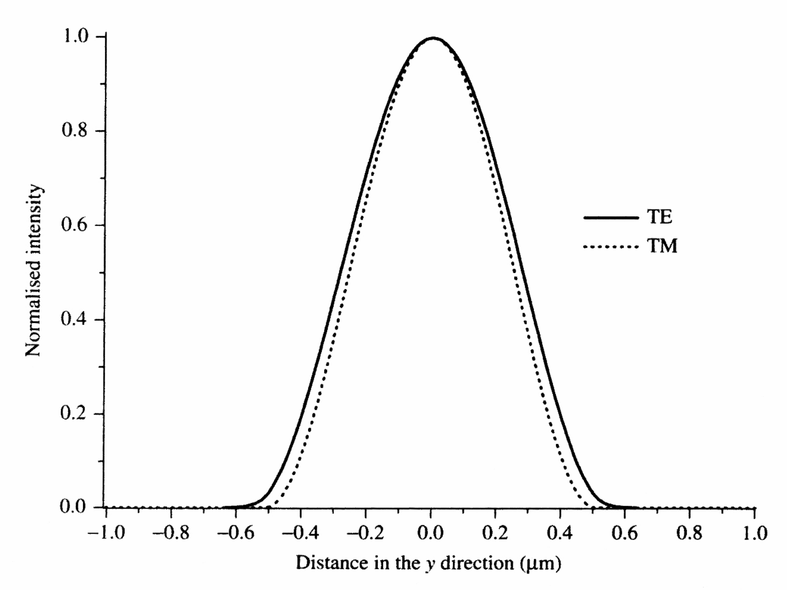

Figure 7.3 TE and TM intensity profiles for a waveguide height of *h* = 1.0 μm

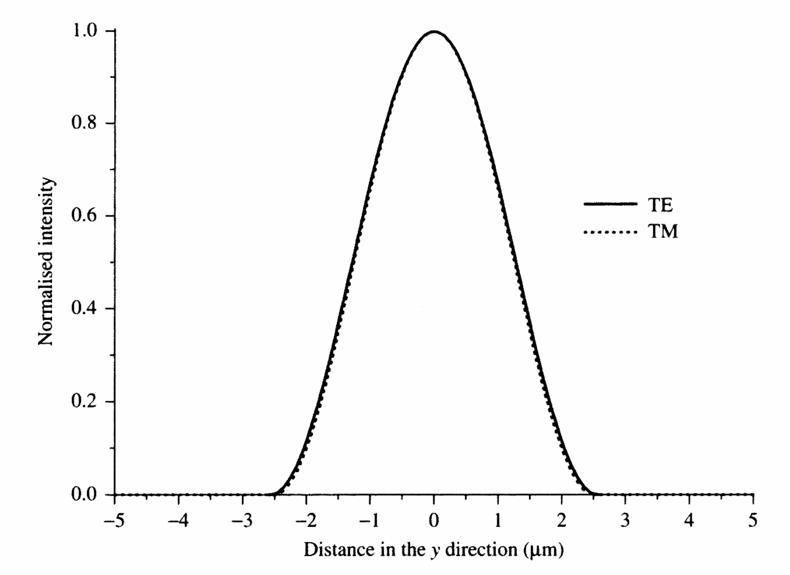

Figure 7.4 TE and TM intensity profiles for a waveguide height of *h* = 5 μm

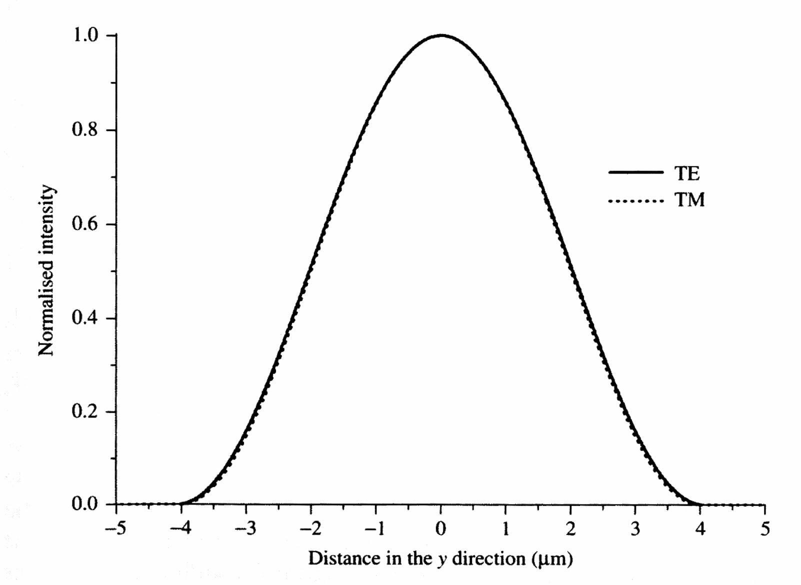

Figure 7.5 TE and TM intensity profiles for a waveguide height of *h* = 8 μm

THE EFFECT OF WAVEGUIDE THICKNESS

- It is clear that in general the confinement of the TE and TM modes is different.
- This means that if the waveguide cladding is lossy in some way, or the core/cladding interface is lossy, then the modes will experience different losses because there is more power in the cladding (and at the interface) for one mode than the other.
- It is also clear that as the waveguide is increased in size, the TE and TM modes become similar, and the polarization dependence is reduced.
- It is also worth noting in passing that the mode profiles presented above are normalized to have unity peak intensity.

THE EFFECT OF WAVEGUIDE THICKNESS

- This has been done so that a direct comparison can be made.
- It is more usual to normalize these profiles to unity power flow, but in general this results in different amplitudes when plotting both profiles on the same axis, and hence visual comparison is more difficult.
- The differences in confinement of the modes can be understood by considering again the graphical solution of the eigenvalue equation, as demonstrated in Chapter 2.
- If we plot both the TE and the TM phase change on reflection for the TM mode is always greater than that for the TE mode.
- Figure 7.6 shows these graphs for the waveguide parameters associated with Figure 7.3, when $h = 1\ \mu$m

THE EFFECT OF WAVEGUIDE THICKNESS

- Since the intersection of the curve of $k_0 n_1 h \cos\theta_1$ and the TE curve is always to the right of the intersection with the TM curve, the TE mode always has a larger propagation angle than the TM mode. Recall that the lateral (y-directed) propagation constant was given by the following equation:

$$k_y = n_1 k_0 \cos\theta_1 \qquad (7.5)$$

- Since θ_1 is larger for the TE mode, then $\cos\theta_1$ is smaller for the TE mode, and hence the propagation constant, k_y, is also smaller.
- Therefore the phase change across the waveguide is also smaller for the TE mode, resulting in the field profiles of Figures 7.2 to 7.5.

THE EFFECT OF WAVEGUIDE THICKNESS

- Note that Figure 7.5, for the largest planar waveguide, suggests that the mode profiles are coincident. This is just a function of the scale of the diagram.
- If we look more closely at the region of one of the core/cladding boundaries, we still see the separation of the modes.
- For example, taking the 8 μm waveguide of Figure 7.5 and 'zooming in' at the upper boundary results in Figure 7.7.
- It is clear, therefore, that increasing the waveguide thickness brings the TE and TM modes closer together in terms of their field profiles.
- However, there is still a finite separation between the degree of con-finement, although in practice the difference may be negligible for some applications.
- The situation is more complex for rib waveguides, and will be discussed further in Section 7.4.

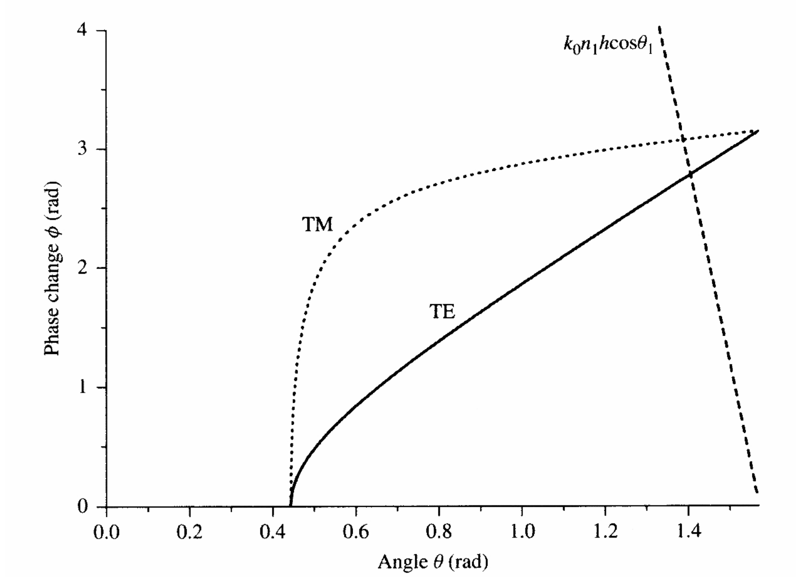

Figure 7.6 Solution of the TE and TM eigenvalue equation for $h = 1\ \mu$m

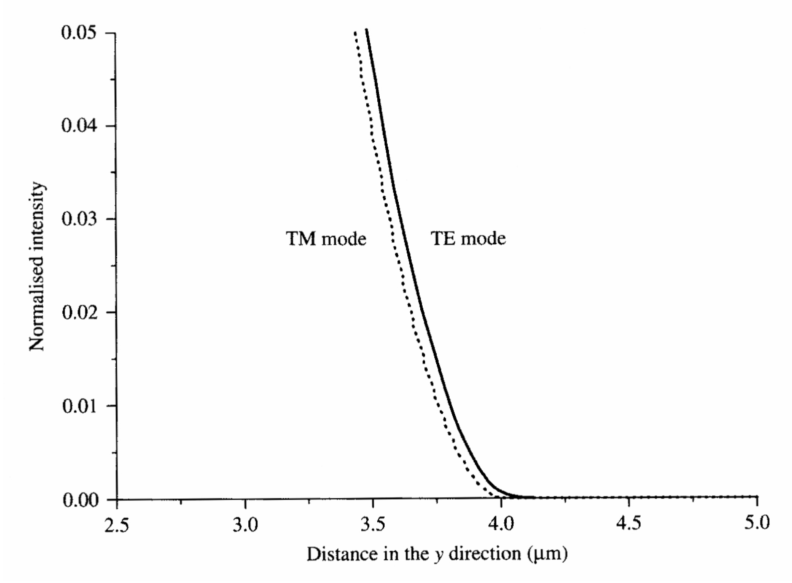

Figure 7.7 Enlarged view of part of the TE and TM mode profiles for *h* = 8 μm

7.2 SURFACE SCATTERING LOSS FOR DIFFERENT WAVEGUIDE THICKNESS AND POLARIZATION

SURFACE SCATTERING LOSS FOR DIFFERENT WAVEGUIDE THICKNESS AND POLARIZA TION

- The previous section demonstrated that TE and TM modes experience different degrees of optical confinement, even in a waveguide fabricated in a material that is nominally isotropic.
- One of the consequences of this is that the power at the waveguide core/cladding interfaces will be different for the two polarizations. Also, because the propagation angles are different, one mode will experience more reflections at the core/cladding interface than the other.
- In turn, this means that the loss due to scattering at the interfaces will also be different, because this loss is related to the intensity at the interfaces, together with the degree of interaction with the interfaces.

SURFACE SCATTERING LOSS FOR DIFFERENT WAVEGUIDE THICKNESS AND POLARIZA TION

- Recall that in Chapter 4 an approximate model of interface scattering was introduced, originally produced by Tien in 1971 [1], and based upon the specular reflection of power from a surface. By considering the total power flow over a given distance, together with the loss at both waveguide interfaces, Tien produced the following expression for the loss coefficient due to interface scattering:

$$\alpha_s = \frac{\cos^3\theta}{2\sin\theta}\left(\frac{4\pi n_1(\sigma_u^2+\sigma_\ell^2)^{\frac{1}{2}}}{\lambda_0}\right)^2\left(\frac{1}{h+\dfrac{1}{k_{yu}}+\dfrac{1}{k_{y\ell}}}\right) \qquad (7.6)$$

where σ_u is the r.m.s. roughness for the upper waveguide interface, σ_l is the r.m.s. roughness for the lower waveguide interface, k_{yu} is the *y*-directed decay constant in the upper cladding (as defined in Chapter 2), k_{yl} is the y-directed decay constant in the lower cladding, and *h* is the waveguide thickness.

SURFACE SCATTERING LOSS FOR DIFFERENT WAVEGUIDE THICKNESS AND POLARIZA TION

- In order to further investigate the polarization-dependent loss of the waveguides of section 7.1, we can evaluate the scattering loss of the fundamental TE and TM modes of each of these waveguides in turn. In order to do this, we must first evaluate the decay constants in the cladding for each waveguide.
- Since the waveguides are symmetrical, the decay constant for the upper cladding, k_{yu}, and the decay constant for the lower cladding, k_{yl}, will be equal. Evaluating these decay constants in turn for waveguides of thickness 0.3 μm, 1.0 μm, 5 μm and 8 μm, and for each polarization, gives the results in Table 7.1.
- Following Chapter 4, if we now let both σ_u and σ_l equal 1 nm, we can evaluate the scattering loss for each fundamental mode, for each nanometer of r.m.s. roughness at the interfaces. Using equation 7.6 we obtain the results in Table 7.2.

SURFACE SCATTERING LOSS FOR DIFFERENT WAVEGUIDE THICKNESS AND POLARIZA TION

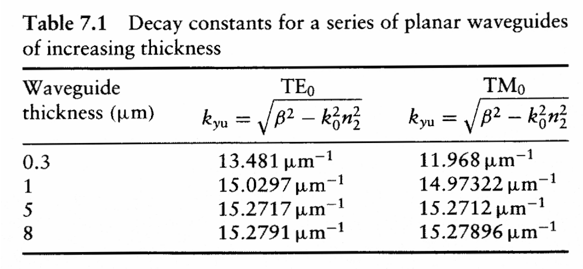

Table 7.1 Decay constants for a series of planar waveguides of increasing thickness

Waveguide thickness (μm)	TE$_0$ $k_{yu} = \sqrt{\beta^2 - k_0^2 n_2^2}$	TM$_0$ $k_{yu} = \sqrt{\beta^2 - k_0^2 n_2^2}$
0.3	13.481 μm^{-1}	11.968 μm^{-1}
1	15.0297 μm^{-1}	14.97322 μm^{-1}
5	15.2717 μm^{-1}	15.2712 μm^{-1}
8	15.2791 μm^{-1}	15.27896 μm^{-1}

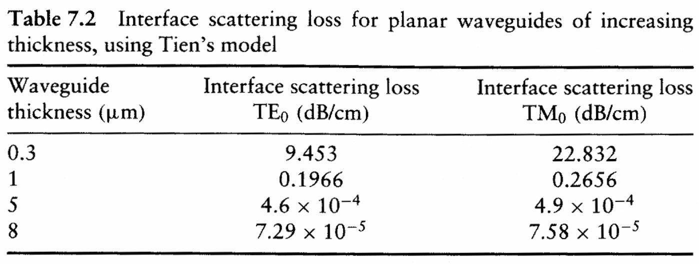

Table 7.2 Interface scattering loss for planar waveguides of increasing thickness, using Tien's model

Waveguide thickness (μm)	Interface scattering loss TE$_0$ (dB/cm)	Interface scattering loss TM$_0$ (dB/cm)
0.3	9.453	22.832
1	0.1966	0.2656
5	4.6×10^{-4}	4.9×10^{-4}
8	7.29×10^{-5}	7.58×10^{-5}

SURFACE SCATTERING LOSS FOR DIFFERENT WAVEGUIDE THICKNESS AND POLARIZA TION

- Notice that despite the TM mode being more tightly confined, accord-ing to Tien's model, it experiences a higher loss.
- This is rather suspicious, and so it is instructive to compare these results with another scattering model, of which there are many.
- If we follow the approach of, for example, Marcuse [2], Lacey and Payne [3], and Ladouceur et al. [4], these authors developed models based upon a correlation function over the length of the waveguide.

SURFACE SCATTERING LOSS FOR DIFFERENT WAVEGUIDE THICKNESS AND POLARIZA TION

- Using an exponential correlation function, a simple model for the loss coefficient results as follows [3,4]:

$$\alpha_s = \Phi^2\left(\frac{h}{2}\right)(n_{\text{core}}^2 - n_{\text{cladd}}^2)^2\left(\frac{k_0^2}{8n_{\text{core}}}\right)\left(\frac{1}{N - n_{\text{cladd}}}\right)\sigma^2 \tag{7.7}$$

where n_{core} is the refractive index of the core, n_{cladd} is the refractive index of the cladding, N is the effective index of the propagating mode, h is the waveguide thickness, and $\Phi^2(h/2)$ is the value of $[Ex(y)]^2$ in the TE case, or $(1/n^2)[Hx(y)]^2$ in the TM case, at the core/cladding interface. In both cases power normalization is used such that $\int_{-\infty}^{\infty} \Phi^2(y)\mathrm{d}y = 1.$

SURFACE SCATTERING LOSS FOR DIFFERENT WAVEGUIDE THICKNESS AND POLARIZA TION

- As would be expected, there are several similarities between equa-tions 7.6 and 7.7, although only the latter explicitly uses the power at the core/cladding interface to evaluate the loss coefficient.
- If we repeat the calculations of loss coefficient for the waveguide parameters of Table 7.2, using the model of equation 7.7, the results in Table 7.3 are obtained.

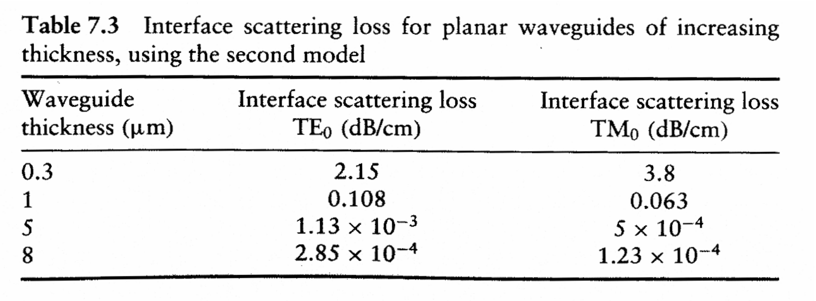

Table 7.3 Interface scattering loss for planar waveguides of increasing thickness, using the second model

Waveguide thickness (μm)	Interface scattering loss TE_0 (dB/cm)	Interface scattering loss TM_0 (dB/cm)
0.3	2.15	3.8
1	0.108	0.063
5	1.13×10^{-3}	5×10^{-4}
8	2.85×10^{-4}	1.23×10^{-4}

SURFACE SCATTERING LOSS FOR DIFFERENT WAVEGUIDE THICKNESS AND POLARIZA TION

- Clearly the results from the latter model are different from those of Tien's model.
- This merely highlights the limitations of various models, and the need to take care in applying the results of specific models to a given situation.
- In particular it shows that the desire to use a simple analytical model, whilst being attractive, is often inherently approximate.
- Comparing the results of Tables 7.2 and 7.3, we see that the agreement is worse when the waveguide is small.
- This is not surprising as many models become inaccurate at dimensions of the order of the wavelength.
- In the present case the latter model is likely to be more accurate as it has been developed in conjunction with real roughness measurements, and is based upon field intensities at the core/cladding interface.
- It also predicts lower losses that more closely resemble the results in the literature.
- In particular, a significant difference between the models is that Tien's model predicts a higher loss from the better-confined TM mode, whereas the model of Ladouceur et al. predicts the opposite.

SURFACE SCATTERING LOSS FOR DIFFERENT WAVEGUIDE THICKNESS AND POLARIZA TION

- The results so far are based upon an r.m.s. interface roughness of 1 nm at the core/cladding interface. By extension we can consider the loss due to a range of values of interface roughness.
- Consider, for example, one of the waveguides above, with a thickness of 1 μm. Let us consider the interface scattering loss for r.m.s. roughnesses of 0.1 nm, 0.5 nm, 1 nm, 10nm and 50nm, using the model of Ladouceur et al. The results are shown in Table 7.4.
- It is also instructive to carry out the same calculation for a larger waveguide, say the 5 μm waveguide.
- The results are shown in Table 7.5.

SURFACE SCATTERING LOSS FOR DIFFERENT WAVEGUIDE THICKNESS AND POLARIZA TION

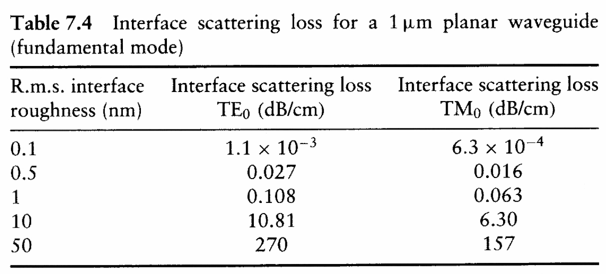

Table 7.4 Interface scattering loss for a 1 μm planar waveguide (fundamental mode)

R.m.s. interface roughness (nm)	Interface scattering loss TE_0 (dB/cm)	Interface scattering loss TM_0 (dB/cm)
0.1	1.1×10^{-3}	6.3×10^{-4}
0.5	0.027	0.016
1	0.108	0.063
10	10.81	6.30
50	270	157

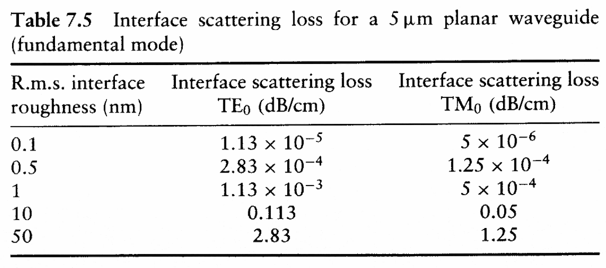

Table 7.5 Interface scattering loss for a 5 μm planar waveguide (fundamental mode)

R.m.s. interface roughness (nm)	Interface scattering loss TE_0 (dB/cm)	Interface scattering loss TM_0 (dB/cm)
0.1	1.13×10^{-5}	5×10^{-6}
0.5	2.83×10^{-4}	1.25×10^{-4}
1	1.13×10^{-3}	5×10^{-4}
10	0.113	0.05
50	2.83	1.25

SURFACE SCATTERING LOSS FOR DIFFERENT WAVEGUIDE THICKNESS AND POLARIZA TION

- From Tables 7.4 and 7.5 it can clearly be seen that the degree of loss is related not only to the polarization, but also to the degree of wall rough-ness, as a function of the waveguide thickness.
- Consequently if a given fabrication process results in an absolute waveguide roughness, the loss is minimized in larger waveguides, as is the polarization-dependent loss.
- It is clear from the foregoing results that the polarization-dependent loss can become important if the interface quality is not kept under control, or if the device is very long.
- For example the interface roughness of the silicon/buried oxide layer of commercially available SIMOX wafers is typically in the range 0.8-3 nm.
- Even if we assume the surface of such wafers is perfectly smooth, the model of Ladouceur et al. suggests a loss ranging from 0.04 dB/cm to 0.57 dB/cm for the fundamental TM mode of a 1 μm waveguide.

- To maintain simplicity, the preceding discussion has focused on planar waveguides, but of course it is also important to consider the scattering loss of three-dimensional waveguides such as rib waveguides.
- In a rib waveguide, the contribution to loss can be increased as compared to a planar waveguide, because the additional etched silicon surfaces are also potential scattering centers due to interface roughness.
- This situation is compounded by the fact that the etch is an additional fabrication step, that must be constantly monitored to ensure that quality is maintained.
- The design of the rib waveguide is also important because the vertical and horizontal surfaces of the rib waveguide may exhibit polarization -dependent loss.
- Consequently, if one surface is likely to be significantly rougher than the other owing to a particular fabrication step, the waveguide may exhibit unacceptable polarization-dependent loss.
- Of course, as the rib waveguide is reduced in dimensions, like the planar waveguide, it will exhibit proportionately more loss, because the mode confinement will reduce.
- This makes consideration of the waveguide roughness even more important.

7.3 POLARIZATION-DEPENDENT COUPLING LOSS

POLARIZATION-DEPENDENT COUPLING LOSS

- Not only will the mode profiles and the scattering loss of the waveguide vary with polarization, but perhaps the most fundamental part of utilizing an optical circuit will also be affected by polarization.
- This is the loss associated with coupling light to the waveguide itself.
- The most usual way of coupling to an optical circuit is via an optical fiber.
- This process was discussed in Chapter 4, where it was noted that the efficiency with which the light is coupled into the waveguide is a function of
  - (i) how well the fields of the excitation and the waveguide modes match;
  - (ii) the degree of reflection from the waveguide facet;
  - (iii) the quality of the waveguide endface; and
  - (iv) the spatial misalignment of the excitation and waveguide fields.

POLARIZATION-DEPENDENT COUPLING LOSS

- There can also be a numerical aperture mismatch in which the input angles of the optical waveguide are not well matched to the range of excitation angles, but this latter term is neglected here.
- Of these parameters, (iii) and (iv) will be the easiest to optimize, although note that they will not be independent of polarization.
- However, we can assume that in a high-quality device the endface is well polished and, for the purposes of this discussion, that perfect alignment is achieved.
- Similarly, if we assume normal incidence of the exciting optical field, the reflection from the endface will be nominally the same for both polarizations, as shown in Chapter 4.
- Consequently, the dominant mechanism affecting the coupling efficiency with regard to polarization is item (i), the overlap between the excitation and modal fields.

POLARIZATION-DEPENDENT COUPLING LOSS

- In order to consider the effect of polarization upon the overlap between the two fields when coupling to a rib waveguide, it is convenient to use a commercially available numerical waveguide simulation package, because an analytical solution becomes difficult owing to the complex mode profile of the rib waveguide.
- In this section of the text, such a simulator has been used to produce a series of curves determining the coupling loss from an optical fiber to a range of rib waveguides, based upon a fixed silicon layer thickness.
- Note that Fresnel reflection from the waveguide endface is not included in this calculation.
- This calculation is more complex than it appears at first sight, because for any given rib width, etch depth and rib height, the optimum alignment will change with the changing mode shape.
- That is, the optimum vertical position for good coupling will in general be different for every waveguide

POLARIZATION-DEPENDENT COUPLING LOSS

- Consequently to find the optimum coupling to any waveguide, it is necessary to scan the input mode position vertically across the input facet.
- If we make the assumption that optimum coupling is achieved for all waveguides, we can then plot optimum coupling for a given rib waveguide height and etch depth, with the variation in rib width.
- For each waveguide height, we can therefore plot a pair of curves (TE and TM) for each etch depth, resulting in a whole family of curves when different etch depths are included.
- Figure 7.8 shows such a family of curves for a silicon overlayer thickness (rib waveguide height) of h = 5 μm, and an input field being the fundamental mode of a silica optical fiber with a core diameter of 5 μm.
- The coupling efficiency is evaluated for each input polarization by monitoring the power in the simulated optical field within the waveguide, after a propagation length of 500 μlm, as a proportion of the launch power. **In** effect this is (approximately) an evaluation of the overlap integral of the modes of the waveguide and the fiber.

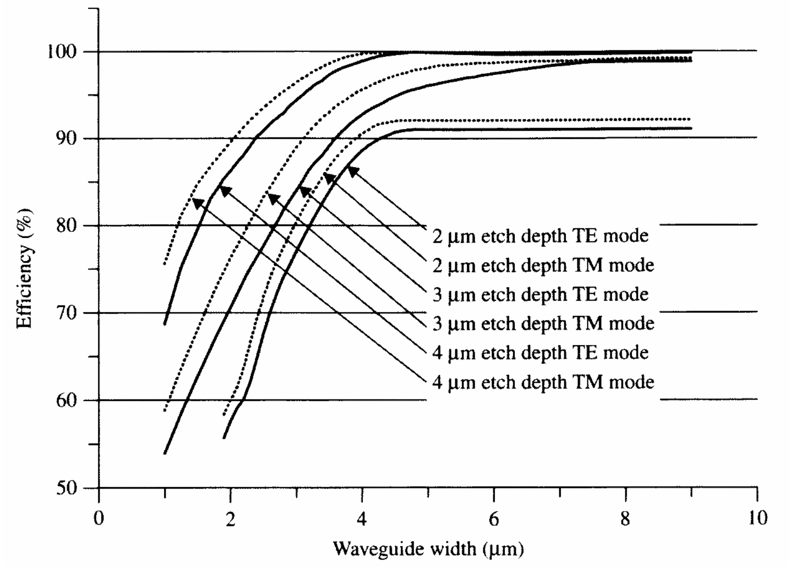

Figure 7.8 A family of curves evaluating coupling efficiency from an optical fiber (5-μm core) to various rib waveguides with height h = 5 μm

POLARIZATION-DEPENDENT COUPLING LOSS

- Individual data points have been evaluated, and trend lines added to guide the eye. It can be seen that the coupling efficiency in most cases is high.
- This is because the mode sizes of the waveguide and fiber are similar. In general the more confined TM mode couples more efficiently than the TE, but when the waveguide width reaches the same order of dimension as the waveguide height the differences are relatively small.
- If we carry out a similar evaluation for less well matched modes, less efficient coupling results.
- This is demonstrated in Figure 7.9. In this case the launch fiber has a core diameter of 9 μm, and the rib waveguide characteristics are unchanged.
- In Figure 7.9 the trends are similar, but efficiency continues rising as the waveguide width increases, as the mode widths of fiber and waveguide become similar.
- Once again the TM mode coupling is slightly more efficient.

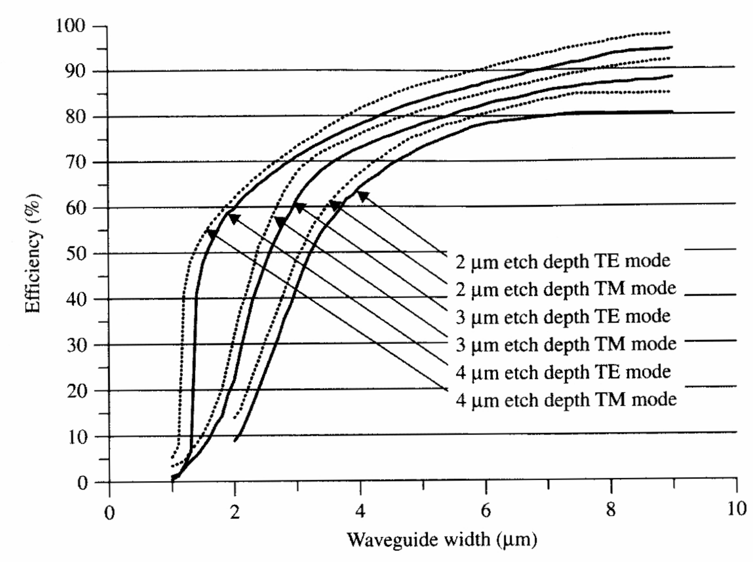

Figure 7.9 A family of curves evaluating coupling efficiency from an optical fiber (9-μm core) to various rib waveguides with height h = 5 μm

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POLARIZATION-DEPENDENT COUPLING LOSS

- Clearly the loss is greater when coupling to the waveguide that is less well matched to the fiber mode.
- There is also a trend for less polarization dependence in wider waveguides, and for waveguides with shallower etch depth.
- However, care should be taken in extracting too much data from these graphs, as coupling efficiency will be related to the mode shapes of all excited modes, and their relative degree of excitation, all of which will change with changing rib geometry.
- Consequently in some cases high-order modes will be well excited and subsequently lost, resulting in lower net coupling efficiency, and in some cases the efficiency of coupling only to the fundamental mode will be high.
- Consequently detailed modeling should be carried out for each specific case to be considered.