Design considerations for devices based upon small SOI waveguides

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Abstract:
With the increased desire to miniaturise devices in silicon photonics comes increased difficulty in producing polarisation independent devices whilst maintaining monomode behaviour. In this paper we discuss the design of such devices, and report supportive experimental results.

Discussion:
Figure 1 shows a schematic of a typical rib waveguide, as well as the commonly utilised labels for rib width (W), etch depth (D), guiding layer height (H), and slab height (r). For large rib waveguides, Soref et al [1], and Pogossian et al [2], have defined geometric design rules for the waveguide to behave as a single mode device. These designs rules can be summarised by equation (1), for waveguides in which $0.5 \le r < 1.0$. In equation (1) Soref et al [1] suggested the value of α should be 0.3, whereas Pogossian et al [2] suggested $\alpha = 0$. However, their analysis was limited to large waveguides, with shallow etch depth.

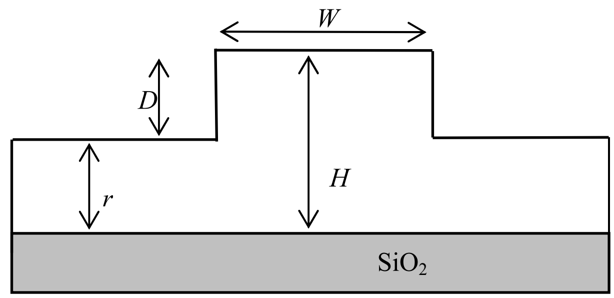


Figure 1 SOI Rib Waveguide

$$\frac{W}{H} \le \alpha + \frac{r}{\sqrt{1-r^2}} \quad \text{.......................................(1)}$$

However, with the trend to smaller devices we wish not only to maintain single mode behaviour in small waveguides, but also to operate in the polarisation independent regime. We have shown previously that for waveguides with cross sectional dimensions of the order of H = 1.5µm or less, that it is necessary to etch deeply ($r < 0.5$) to equalise the TE and TM propagation constants [3]. Furthermore, in these small waveguides, the modal solutions become dominated by the boundary conditions, and the single mode cut-off condition for TE and TM modes is significantly different, and cannot be represented by a single equation such as equation 1 [3]. To consider this in more detail, we have simulated the variation of three different values of guiding layer heights (H), of 1.0µm, 1.35µm, and 1.5µm. By evaluating the TE and TM propagation constants for a series of waveguide widths and etch depths, the Zero Birefringence (ZB) locus can be determined for each guiding layer height. In the simulations, the waveguide height (H), etch depth (D), and slab height (h) were kept constant whilst increasing the waveguide width in increments of 0.01µm to find the boundary between single-mode and multimode behaviour. The iteration of the simulation was repeated with different values of the slab height to waveguide height ratio (parameter r). Hence the process is one in which we gradually increase the waveguide width until a second-order mode is guided. The boundary of the single/multimode can therefore be determined by computing the minimum waveguide width at which the first higher-order mode is supported by the waveguide structure. Figure 2 summarises the data for both zero birefringence and single mode conditions. Also included on these graphs are the extrapolated single mode conditions from both Soref at al [1], and Pogossian et al [2], for reference. However, it is clear that neither of these design rules that are reasonable for large waveguides, are suitable for small deeply etched waveguides. For brevity, only two graphs are included in Figure 2, for guiding layer heights of H=1.0µm, and H=1.35µm.

It can be seen from Figure 2 that it is possible to achieve single mode operation at both polarisations whilst maintaining polarisation independence for each of the waveguide heights used. In order to satisfy both the requirements, we must choose a point on the birefringence free locus that is below the single mode boundary for both quasi-TE and quasi-TM modes. However, it should be noted that the trend lines are approximate because they are the result of curve fitting, and therefore, for a specific design, data points should be used instead of the trend lines. It is interesting to note that the intersection between the birefringence free locus and the quasi-TE graphs determines the limit of the waveguide width to guide only the fundamental TE mode, but multiple TM modes. For example, the maximum values of rib width (W) are 0.77µm, 0.98µm and 1.05µm for waveguide heights (H) of 1.00µm, 1.35µm and 1.50µm respectively, to satisfy the quasi-TE single mode condition and the birefringence free condition. However, if we also wish to satisfy the single mode condition for TM polarisation, narrower waveguides are required. In this case the waveguide widths must be 0.52µm, 0.83μm, and 0.92μm respectively. The crossing points for the two polarisations between the birefringence free condition and both single mode boundary lines are closer to each other as the waveguide height is increased.

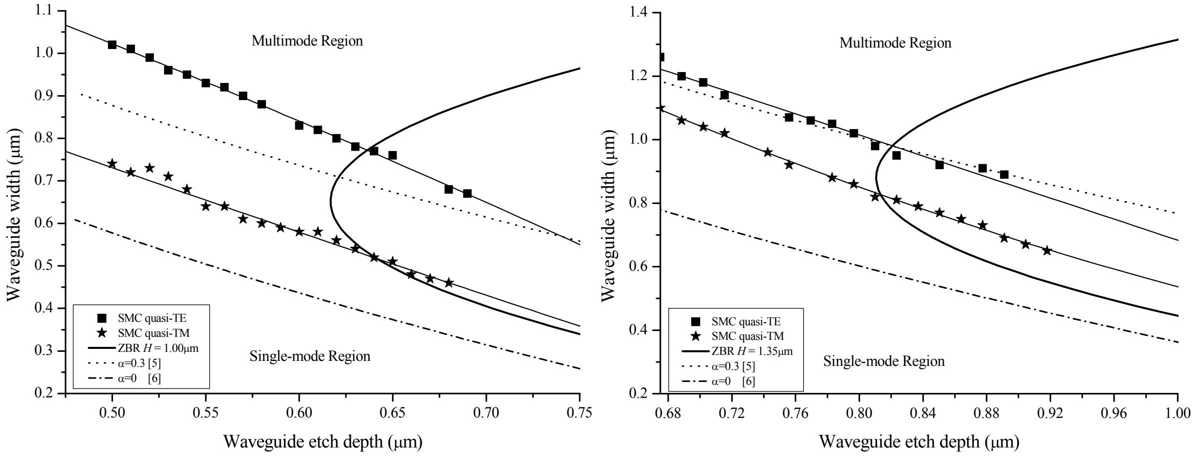


Figure 2 Trend and boundary lines for single mode cut-off dimensions and zero birefringence as a function of waveguide dimensions for an operating wavelength of λ=1550nm for (a) H=1.00μm (b) 1.35μm

Hence it is easier to satisfy both conditions for a waveguide height of 1.35μm compared to a waveguide with a height of 1.00μm. As the etch depth (*D*) increases (or parameter *r* decreases), the waveguide width must also be reduced to maintain only single-mode operation for a designated polarisation. The results of figure 2 give us confidence in the possibility of achieving SOI waveguides satisfying both the single mode and zero birefringence requirements, as demanded by many applications. However, in some cases the relevant requirement of the waveguide width may be too narrow for fabrication purposes and impractical when coupling light into the small waveguide structure. The single mode condition for these small waveguides with deep etch depth ($r < 0.5$) is effectively limited by the boundary condition set by the quasi-TM mode. Hence we have produced a generalised equation in terms of waveguide dimensions, following the notation used in [1,2], that is a fit to the quasi-TM data:

$$\frac{W}{H} \leq 0.05 + \frac{(0.94 + 0.25H)r}{\sqrt{1-r^2}} \qquad \ldots\ldots(2)$$

$$0.3 < r < 0.5 \quad \textit{and} \quad 1.0 \leq H \leq 1.5$$

The validity of this equation has been considered experimentally by fabricating devices based around the guiding layer height of H=1.35μm. Because it is sometimes difficult to experimentally determine whether higher order modes are propagating by observing mode profiles alone, we have utilised ring resonator structures as mode selectors. This is effective because higher order modes will propagate with similar but different propagation constants to the fundamental mode, and hence will resonate at slightly different wavelengths. Therefore we can determine higher order resonant modes by looking at the variation from the expected resonances, and departures from the expected free spectral range. Similarly we can easily determine whether the ring resonators are polarisation independent by considering whether quasi TE and quasi TM mode resonances are coincident. However, the effect of the ring resonator approach is also limited to modes for which the coupler of the ring resonator works effectively. Therefore we have considered a series of ring resonators with similar but slightly different geometrical dimensions, in the critical parts of figure 2 in terms of both the single mode condition and the zero birefringence locus. Figure 3 below reproduces figure 2(b), with the addition of four data points representing four different ring resonators that have been evaluated experimentally. Ring resonator data has been collected in the form of spectral scans for both TE and TM polarisations. Where there are multiple resonances in any spectral scan within a single free spectral range, this is clear evidence of multimode waveguides. However, the absence of multiple resonances is not clear evidence of single mode behaviour because this could simply mean that the higher order modes do not couple well to the resonant rings. Nevertheless, such data is supportive of the notion of single mode behaviour, albeit not definitive. If we consider the four data points in turn, figure 4a shows a ring resonator scan representing data point 1, and suggests that this device is single mode for TE and multimode for TM.

Figure 4b shows a ring resonator scan representing data point 2, and the multiple resonances indicate multimode behaviour for both TE and TM polarisations. For brevity data is not included for the remaining data points 3 & 4, but scans suggested that datapoint 3 represents a ring resonator that is single mode for both TE and TM polarisations, although the TE data resonance was not as strong as we would have expected for the fundamental mode suggesting that a higher order mode could be missed when the signal to noise ratio is reduced. Finally data for datapoint 4 clearly suggested multi mode behaviour for both TE and TM polarisations.

At first sight this data does not fit well with the predictions of figure 2b, but of course no account of stress has been taken in the simulations of figure 2b.

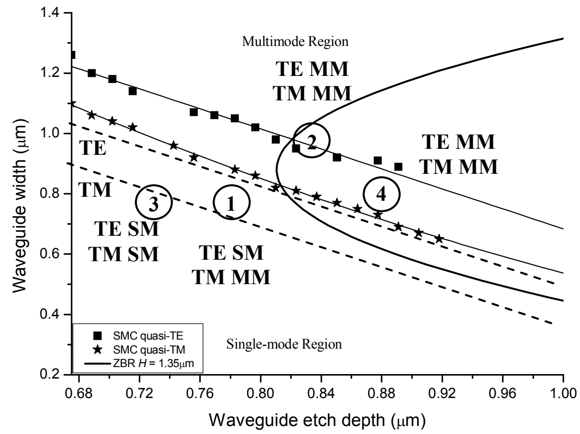
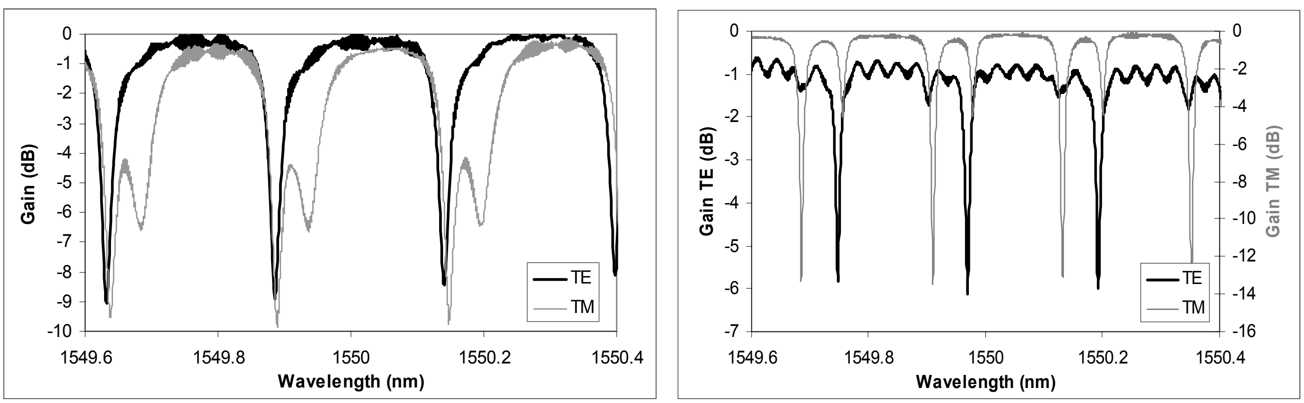


Figure 3 Location of experimental datapoints with respect to the single mode and birefringence free conditions



(a) (b)

Figure 4 Experimental data corresponding to (a) datapoint 1 on figure 2b, and (b)datapoint 2 on figure 2b

Ye et al [4] reported a significant contribution to changes in the effective index due to the presence of oxide claddings on SOI waveguides. If, for example such a cladding results in a compressive stress, then an increase in effective index would be expected, and the single mode conditions of figure 2b would effectively move downwards. If these lines move to the positions indicated on figure 3, by the dotted lines, then the experimental data becomes consistent with the modelling. We are currently evaluating this possibility, and will report any progress at the Group IV Photonics conference.

Conclusion:

We have considered both the modal and polarisation characteristics of small waveguides in SOI, and have developed a design equation for single mode behaviour, as well as modelling the zero birefringence condition. These conditions have been examined experimentally for a limited number of design variants, using a ring resonator structure to identify modal and polarisation properties. For the devices tested, the agreement was not good until the effect of cladding induced strain is considered, although a more comprehensive study is required to fully justify use of the design equations presented here.

References:

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