Lateral Leakage Loss of TM-like modes in Silicon-on-Insulator (SOI) Ridge Waveguides

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Recently, the existence of waveguide width dependent lateral leakage loss of the TM-mode in SOI ridge waveguides has been observed experimentally and a regular pattern in the minima of the said loss has been reported. Following this, a strategy for reducing this loss and a broadening of the minima of these losses has been reported. In what follows, we revisit this interesting phenomenon. We outline the mechanism by which this leakage loss occurs. Next, we proceed to investigate the effects of waveguide width and wavelength on the leakage loss and give an outlook for future possibilities.

Introduction

SOI waveguides possess many desirable properties which make them suitable for high-density integration on a single chip. SOI technology has been very successful because it utilises a high index contrast (small components) material system and is compatible with CMOS fabrication technology (i.e. it is cheap). An interesting class of SOI waveguide is the quasi planar ridge waveguide [1] which is suitable for active SOI devices like modulators and/or light-emitting sources. Unfortunately, for certain practical geometries, the TM-like mode of ridge waveguides exhibits lateral leakage loss. Recently in the literature, the existence of this leakage loss and its dramatic (cyclic) dependence on the width of the ridge waveguide has been observed experimentally [2]. In yet another study [3], a strategy for reducing and broadening of the minima of these losses is reported. In this work, we study the dependence of the leakage loss on the wavelength. We also look at the way in which the wavelength of the light used can affect the leakage loss for a fixed waveguide width. Finally, we present an outlook for future work.

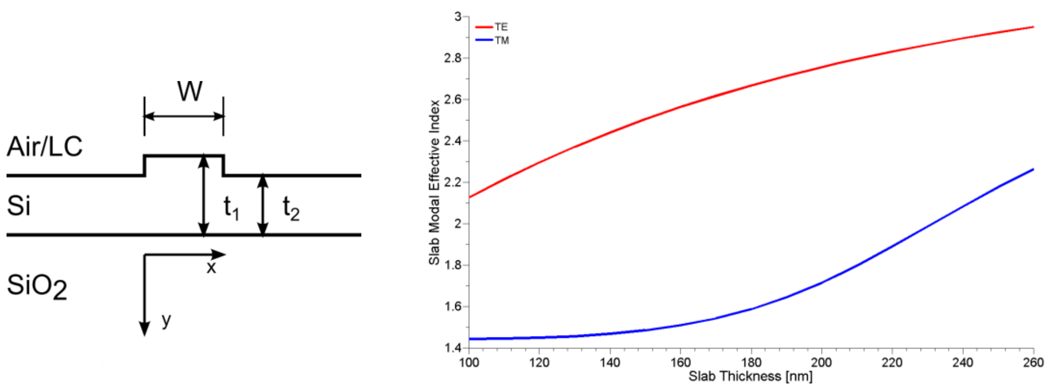

Figure 1: (Left) Problem geometry, the positive z-direction is perpendicular to the page. (Right) Effective index versus slab thickness for an SOI slab waveguide. Plot is obtained using a fully vectorial finite element solver; the operating wavelength is 1550 nm.

Lateral Leakage Loss Mechanism

Before proceeding any further a brief review of the mechanism for lateral leakage loss is in order. The optical fields in SOI ridge waveguides are confined in the *y*-direction by the index mismatch between air, silicon and silica (See fig. 1). In the *x*-direction, confinement is provided by the step discontinuity in silicon. For propagation at an angle to the *z*-axis, the TE (resp. TM) mode gets additional small H_x and E_z (resp. E_x and H_z) components as it bounces off the ridge boundaries [4]. Consequently, we have TE-like and TM-like modes in such waveguides; with TE-TM (and TM-TE) mode conversion occurring at the ridge sides. Mode conversion can lead to lateral leakage loss if certain conditions are satisfied. In each case, we must examine the graph on the right in fig.1 to determine which modes are evanescent in the cladding.

For a TE-like propagating ridge waveguide mode, the TE field must necessarily be laterally evanescent in the ridge waveguide cladding. In general, the propagation constant of the TM mode in a slab waveguide with thickness t_2 is lower than that of the corresponding (same order) TE mode for a slab waveguide with thickness t_1. Hence TM fields resulting from TE-TM mode conversion are evanescent. Consequently, the TE-like modes show no lateral leakage loss.

For a TM-like propagating ridge waveguide mode, the TM field in the cladding must be evanescent as well. However, the propagation constant of the TE mode in a slab waveguide with thickness t_2 is larger than that of the corresponding TM mode for a slab waveguide with thickness t_1. Hence TE fields which arise due to TM-TE conversion at the ridge boundary are not evanescent. These TE fields can be phase matched to a laterally propagating TE slab mode at an angle θ in the lateral slab cladding region [2].

Consequently, the TM like mode in SOI ridge waveguides exhibits lateral leakage loss. This is depicted graphically in a so called *k*-vector diagram in fig. 2.

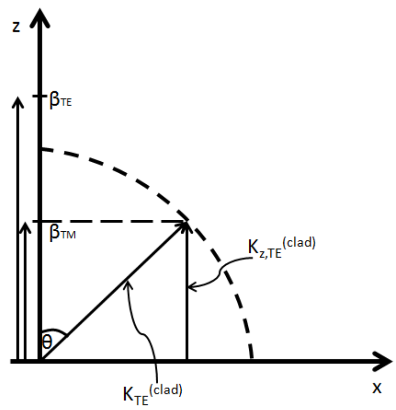

Figure 2: K-vector diagram showing how a TM-like mode can become phase matched to a TE slab mode propagating in the lateral cladding

Following the treatment presented in [2]; when a TM mode bounces off the ridge wall, it generates small transmitted and reflected TE waves which are approximately equal in magnitude but π radians out of phase. Each new transmitted TE wave combines with a previously reflected TE wave which has traversed the ridge waveguide and hence acquired an additional shift of $K_{x,TE}W$. Where W is the ridge waveguide width. If the phase shift for a single traverse of the TE wave in the ridge waveguide core is an integer multiple of 2π, then both TE waves will interfere destructively. This indicates that the leakage loss of the TM mode is width dependent, and the minima in leakage loss satisfy the resonance-like condition $K_{x,TE}W=2m\pi$, which can also be written as;

$$W = \frac{m\lambda}{\sqrt{{n_{eff,TE}}^2 - {N_{eff,TM}}^2}}, \quad m = 1,2,3 \ldots \tag{1}$$

Where $n_{eff,TE}$ is the effective index of the TE mode of a slab waveguide with thickness t_1 and $N_{eff,TM}$ is the effective index of the guided TM ridge waveguide mode. Thus for a fixed wavelength, we expect the TM-like mode to show significant leakage loss except for waveguides with widths satisfying equation (1) above. Another interesting consequence of (1) is that, the leakage loss is wavelength dependent for a fixed ridge waveguide width. We will investigate this effect further in this study; and this especially for widths where we expect lower losses.

Simulation

In order to compute the lateral leakage loss for a given ridge waveguide, we solve for the supported modes using a modal solver implemented in the commercial finite element based software package COMSOL Muliphysics. The solver returns a complex refractive index for each mode; the leakage loss can be computed from the imaginary part of the refractive index. The simulation domain is shown below.

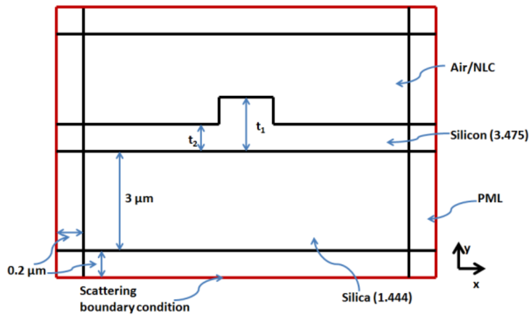

Figure 3: Rough sketch of the simulation set-up.

We start by simulating three cases; $t_1 = 205$ *nm*, $t_2 = 190$ *nm*, $t_1 = 220$ *nm*, $t_2 = 190$ *nm* and $t_1 = 220$ *nm*, $t_2 = 150$ *nm*. The first case corresponds to the design considered in previous studies. The third case is an experimentally realisable design, it can be fabricated at our lab.The ridge width is varied from 0.5 µm to 2.5 µm in steps of 0.02 µm and the operating wavelength is set at 1550nm. The results are shown in fig. 4 below. Increasing the ridge height (t_1-t_2) leads to an overall increase in the leakage loss but the loss minima remain essentially the same.

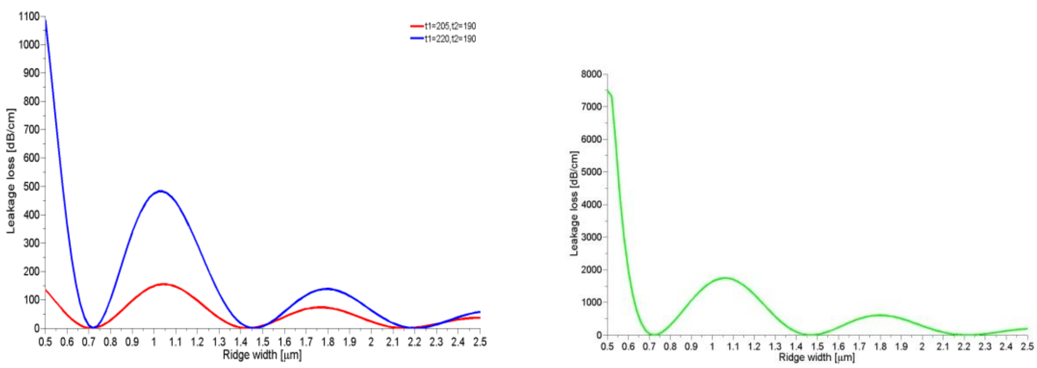

Figure 4: Leakage loss of SOI ridge waveguides. (Left)For t1=205 nm, t2=190 nm the leakage loss minima occur at 0.72 µm, 1.44 µm, and 2.16 µm. For t1=220 nm, t2=190 nm the leakage loss minima occur at 0.72 µm, 1.46 µm, and 2.20 µm. (Right) For t1=220 nm, t2=150 nm leakage loss minima occur at 0.72 µm, 1.46 µm, and 2.22 µm.

The first order loss minima are identical for all three designs. We consider the experimentally realizable design and study the wavelength dependence of the leakage loss for waveguide widths around this minimum. We consider waveguides with widths of 700nm, 720nm and 740nm respectively. For each of these the wavelength is ramped from 1545nm to 1590 nm. We notice the wavelength dependence of the leakage loss can also be quite dramatic.

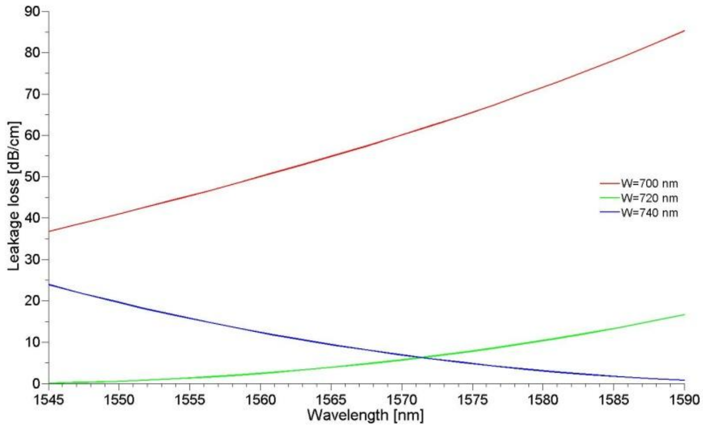

Figure 5: Variation of the Leakage loss with wavelength for fixed ridge waveguide widths.

We notice a variation of at least 15 dB/cm (for the best case, i.e. W = 720 nm), over a wavelength range of 45 nm. For a waveguide width of 720 nm, the loss for light with wavelength equal to 1590 nm is larger than that at 1545 nm by a factor of 32. This is a drastic change which must be taken into account during the design of such waveguides.

In our most recent work, we have looked at the possibility of actively tuning the location of the loss minimum both in waveguide width (for a fixed wavelength) and in wavelength (for a fixed waveguide width). We plan to elaborate on this in a future report.

Conclusion

To summarize, we have introduced the concept of waveguide width dependent leakage loss in TM-like modes of SOI ridge waveguides. Next, we have explained the mechanism by which this loss arises. We followed up on that by calculating the loss curves for various ridge waveguide designs. Finally, we have shown how the loss in these waveguides is also dependent on the wavelength and that this wavelength dependence can also be quite dramatic.

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