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ABSTRACT

In this paper, we investigate athermal and low propagation loss silicon-on-insulator (SOI) rib waveguides. Propagation losses have been modeled for different dimensions of ridge waveguides achieving good agreement with experimental measurements. At certain waveguide widths, it is possible to obtain low propagation losses for both TE (transverse electric) and TM (transverse magnetic) modes. Racetrack ring resonator structures based on ridge waveguides covered by a polymer have been fabricated, aiming for an athermal design and therefore, a very small temperature dependent wavelength shift. Design guidelines for temperature insensitive and small propagation loss ridge waveguides are presented in this paper together with experimental data.

Keywords: Silicon-on-insulator, athermal waveguides, low loss waveguides, mode coupling, near infrared.

1. INTRODUCTION

In the last few years there has been an increased challenge to achieve temperature stability of silicon photonic devices, which is one of the key obstacles to development of viable commercial optoelectronic products[1-8]. Low loss silicon waveguides have also been intensively investigated in recent years due to their importance for integrated photonic circuits[9-19]. Interferometric devices such as spectrometers, Mach-Zehnder interferometer, ring resonators, arrayed waveguide gratings (AWGs), modulators and Bragg grating filters have been studied by a number of researchers to overcome high temperature dependent wavelength and phase shifts which occur due to the temperature dependence of the material's refractive index[3-5].

A heater or thermoelectric cooler can be used for on-chip temperature control, however, this demands a large device foot-print and dramatically increases the cost and power consumption. Use of the thermal stress effects to compensate or amplify the temperature sensitivity of optical devices is possible for materials with low thermo-optic effect and a large elasto-optic effect[1]. Thermal stress effects cannot be used in silicon since the material's refractive index change due to stress is much smaller than the change caused by the thermo-optic effect. Adjusting the refractive index of silicon by control of the carrier density is also not efficient method due to power consumption and the induction of losses[2]. Materials with negative thermo-optic coefficients, such as polymers, represent a possible solution of the problem[20-26]. Negative thermo-optic coefficients of the polymer cladding can compensate the large positive thermo-optic coefficient of the silicon core, thereby providing an athermal design. However, propagation losses for such waveguides are relatively high.

The reduction of loss in optical waveguides represents a challenge due to their importance for on-chip optical networks. Typical losses for ridge waveguides with large cross section (1-3 μm) at the operating wavelength of 1.55μm are 0.2dB/cm[12]. Strip waveguides with small cross section area (~0.11μm^2) exhibit much higher losses (1-2dB/cm) and the losses increases exponentially when the waveguide width decreases[6]. The optical losses come from the scattering loss and absorption sites caused by the fabrication technology. In order to reduce the propagation losses, small cross sectional etchless ridge waveguides have been recently investigated and small losses for TE (transverse electric) mode, of only 0.3dB/cm have been demonstrated[12].

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In this paper, we investigate silicon-on-insulator (SOI) rib waveguide structures and propose design rules to achieve low propagation losses and athermal behavior. Using the LOCal Oxidation of Silicon (LOCOS) technique, submicron waveguides with minimal roughness at the Si/SiO_2 interface can be fabricated achieving low propagation loss of 0.1dB/cm for TE polarisation[11], whilst the losses for TM (transverse magnetic) polarisation are usually higher. We have modeled propagation losses for the TM mode, for different dimensions of rib waveguides, achieving good agreement with experimental measurements. At certain waveguide widths, it is possible to obtain low propagation losses for both TE and TM modes. Polymers that have a negative thermo-optic coefficient are used for the top cladding, to compensate for the positive thermo-optic coefficient of the waveguide core, resulting in an athermal design. Significant reduction of temperature dependence can be achieved by using appropriate waveguide dimensions and adjusting the waveguide cross-section. Racetrack ring resonator structures based on rib waveguides have been fabricated aiming for an athermal design and therefore, for a very small temperature dependent wavelength shift (TDWS). Design guidelines for temperature insensitive and low propagation loss ridge waveguides are presented in this paper.

The paper is organized as follows. Section 2 describes the design rules for low loss waveguides while Section 3 discusses the temperature insensitive design of SOI ridge waveguides. Concluding remarks are given in Section 4.

2. LOW LOSS WAVEGUIDES

In order to reduce optical losses in the ridge waveguides we have used a well-established VLSI technique of the LOCal Oxidation of Silicon (LOCOS) for waveguide fabrication. The technique has been widely utilised in the fabrication of microelectronics components. By using this approach, waveguides with minimal roughness at the Si/SiO_2 interface can be fabricated, thus reducing the propagation loss.

We have fabricated LOCOS waveguides in the sub-micrometer range starting from a p-type material with a 1500nm thick silicon overlayer, and a 2.8µm buried oxide layer. The wafer was thinned using thermal oxidation and subsequently etched in buffered HF to reduce the overlayer thickness to around 700nm. A 40nm SiO_2 layer and a Si_3N_4 masking layer of 80nm were deposited by Low Pressure Chemical Vapor Deposition (LPCVD). Trenches in the Si_3N_4 layer were then defined by photolithography and plasma etched. The structure was subsequently wet-oxidized to produce a 410nm thick SiO_2 layer in the unmasked trench areas. Finally, the Si_3N_4 layer was removed to leave an optical waveguide between the oxidized trenches[11].

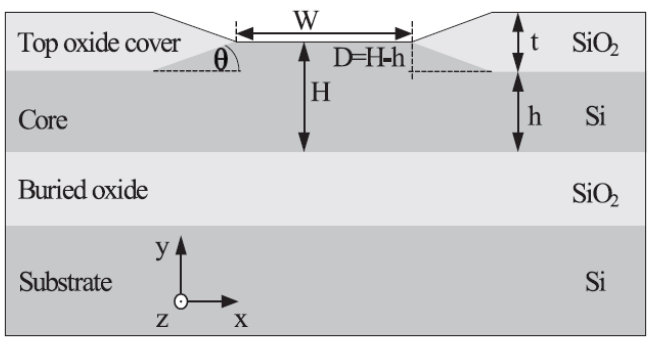

Figure 1. LOCOS waveguide cross-section view: t is the top oxide layer thickness, H is waveguide height, D (D=H−h) is etch depth, W is waveguide rib width and θ is the rib sidewall angle.

Figure 1 represents the cross section view of a LOCOS waveguide. The typical height of the fabricated waveguides was H=770 nm, the slab height was equal to h=600nm while the sidewall angle was equal to $\theta=27^o$. Measured propagation losses at the operating wavelength of 1.55µm for TE polarisation were 0.1dB/cm[11], while the TM polarization has experienced much higher losses (Figure 2). In this study we have employed the full vectorial complex finite mode matching (FMM) technique[27] to analyse the lateral leakage losses in this structure at the operating wavelength of 1.55µm. The main advantage of the mode matching technique over other numerical methods is that the computational window is fully open in the lateral direction. Therefore, the lateral leakage can be modelled accurately[13-16].

Figure 2 shows the comparison between the experimental and measured data. The propagation losses for the TM mode show exponential behavior and a decrease as the waveguide width at the bottom of the rib increases. The main reason for high losses and small oscillations that occur, is polarisation conversion between TM and TE modes as well as lateral leakage which occurs in shallow etched waveguides[14].

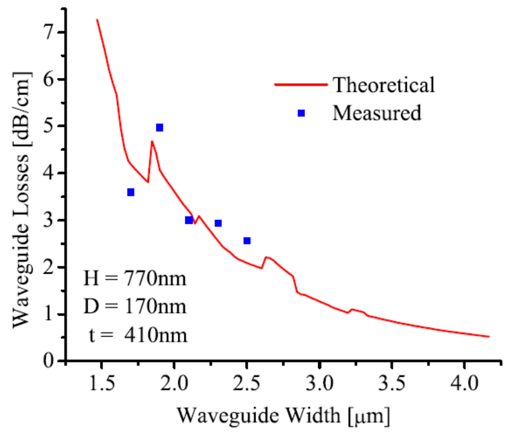

Figure 2. Experimental and theoretical values for waveguide losses as a function of waveguide width (at the bottom of the rib) for TM mode at an operating wavelength of λ=1.55μm (H=770nm, D=170nm, t=410nm, θ=27°).

The same theoretical model has been applied in the analysis of a ridge waveguide with a height equal to H=205nm and an etch depth equal to D=15nm, since experimental results for this structure show certain waveguide dimensions at which small losses for the TM mode can be achieved[14]. The oscillations occur at certain waveguide widths (Figure 3), with a period of 0.72μm, while the first two minima occur at 0.72μm and 1.44μm which was verified by previously reported experimental results[14].

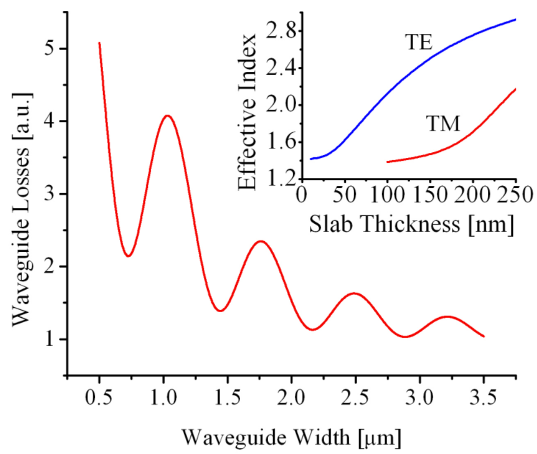

Figure 3. Simulated results for propagation losses for TM mode as a function of waveguide width in SOI rib waveguide (H=205nm, D=15nm, t=0, θ=90°, λ=1.55μm); inset: Effective mode indices for TE and TM mode as a function of slab thickness. Simulation shows good agreement with data reported in [13].

The study of TM-TE mode coupling has been investigated by a number of researchers in recent years since a number of key sensors and active component designs benefit from TM mode operation[14-19]. At the ridge boundaries, the incident TM mode produces a TE component of the field. Destructive interference occurs at certain waveguide widths and can be described by the following equation[14-19]:

$$W = \frac{m\lambda}{\sqrt{\left(n_{eff,TE}^{core}\right)^2 - N_{eff,TM}^2}}, \tag{1}$$

where W is the waveguide width, m is a positive integer, λ is the operating wavelength, and the last two terms represent the slab effective index of the TE mode in the waveguide core and modal effective index of the TM mode. The simulated results from Figure 3 match the result from equation (1) in terms of the value of W for which small losses can be achieved[14]. A small variation of equation (1) has been recently reported[15] but it gives a small shift (~10nm) in waveguide width at which small losses can be achieved.

Figure 4 shows propagation losses for the TM mode for a LOCOS waveguide with H=400nm, variable etch depth and variable top oxide cover thickness. Due to TE-TM mode conversion at the ridge sidewalls, at certain waveguide widths it is possible to achieve small propagation losses for the TM mode. It can be seen that a waveguide width of 2.5μm can provide TM mode losses of less than 0.2dB/cm according to our theoretical model.

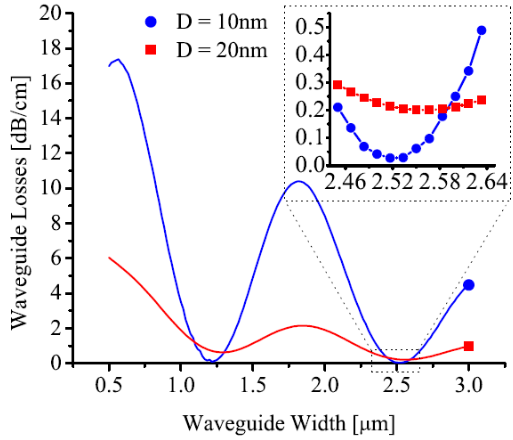

Figure 4. Simulated results for waveguide losses as a function of waveguide width for TM mode (H=400nm, t=2.5D, $\theta=90^o$, $\lambda=1.55\mu m$); inset: Enlargement of the results for waveguide widths around W=2.5μm where minimum waveguide losses can be achieved.

3. ATHERMAL WAVEGUIDES

Recently, there has been an increased interest in athermal waveguides since small temperature variations can cause significant changes in the refractive index, resulting in significant performance deterioration of photonic devices and systems. In particular, high Q ring resonators are very sensitive to temperature variations.

Ye et al. have derived an analytical equation for channel waveguides[23]. The reduction of temperature dependent wavelength shift (TDWS) to a value of 11.2pm/K (in the temperature range of 25-37^{o}C) has been experimentally demonstrated in the racetrack ring resonator using polymers from the acrylate family as a top cladding[28]. Polymethylmethacrylate (PMMA) is also often used[5,20] because of its high transparency and low birefringence, but it has disadvantages such as poor thermal stability and high moisture absorption[26]. Polysiloxane hybrid polymers are very attractive due to low cost and good optical properties, but their disadvantage is higher loss[22]. Lee et al.[21] have used polymer WIR30-490 as a cladding material in SOI strip waveguides and have demonstrated TDWS reduction to the value of 5 pm/K in the 20-80^{o}C temperature range for TM mode. The same polymer was used as a cladding material in a slot waveguide structure[2], where significant reduction in TDWS of ring resonators has been achieved for TE mode (in the 25-75^{o}C temperature range). Teng et al.[6] have used PSQ-LH polymer as an overlayer of a silicon wire to reduce the TDWS of a racetrack resonator, however, propagation losses of 50dB/cm were measured.

To obtain athermal silicon waveguides, an SOI rib waveguide with height of 220nm, waveguide width of 300nm and etch depth of 50nm is used in our fabrication process. The Scanning Electron Micrograph (SEM) of a fabricated racetrack ring resonator is shown in Figure 5. The ring radius is equal to 5μm, while the coupling length is equal to 2μm.

A tunable laser with a wavelength range from 1545 to 1560nm has been used in the experiment. To couple light into and out of the SOI ridge waveguide from a polarization-maintaining lensed-fiber, shallow etched (70nm) gratings were fabricated near the edge of each waveguide. This kind of grating has polarization selectivity and therefore the transmission spectrum measured is for TE polarisation[6] only. The output light is collected by an objective lens and focused on an IR detector. In order to measure the transmitted spectrum at different temperatures, the sample was mounted on a heating system to control the chip temperature. The TDWS for the racetrack ring resonator with an air cover was in the 33-55 pm/K range whilst the measured propagation losses for straight ridge waveguides were 4.9dB/cm. We believe that TDWS can be reduced significantly when a polymer cover is used.

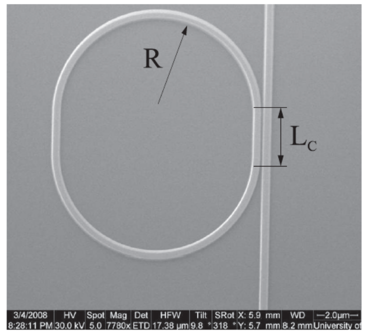

Figure 5. Top view of the racetrack resonator. Ring radius is equal to R=5µm, while the coupling length was equal to L_C=2µm.

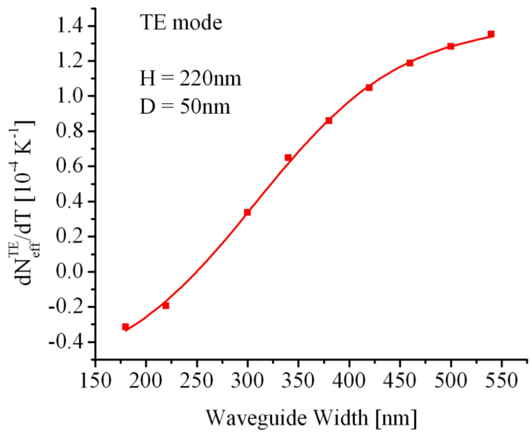

Figure 6. Simulated effective thermo-optic coefficients for TE mode as a function of waveguide rib width with polymer layer on the top (H=220nm, D=50nm, θ=90°, $t_{polymer}$=1000nm).

The finite element method (FEM) was used to find the waveguide parameters at which the polarisation independent condition for TE mode can be achieved[29]. Poly-dimethylsiloxane (PDMS) was modelled as a cladding material since it has negative thermo-optic coefficient which can compensate the positive thermo-optic coefficient of the silicon core. The waveguide widths form 180 to 540 nm were scanned and corresponding change in the modal effective index for TE mode (N_{eff}^{TE}) was plotted. From theoretical calculations (Figure 6), the waveguide width at which an athermal condition can be achieved is 250nm while for the 300nm waveguide width the temperature dependence of the modal effective index for TE mode is predicted to be around $0.2x10^{-4}K^{-1}$.

4. CONCLUSIONS

In this paper, we investigated silicon-on-insulator ridge waveguide structures and proposed design rules to achieve low propagation losses and athermal behaviour. Using the LOCal Oxidation of Silicon (LOCOS) technique, submicron waveguides with minimal roughness at the Si/SiO_2 interface can be fabricated achieving low propagation loss of 0.1dB/cm for TE polarization, whilst the losses for TM polarization are usually higher. We have modelled propagation losses for the TM mode, for different dimensions of rib waveguides, achieving good agreement with experimental measurements. At certain waveguide widths, it is possible to obtain low propagation losses for both TE and TM modes. The PDMS polymer that has a negative thermo-optic coefficient is modelled for the top cladding, to compensate for the positive thermo-optic coefficient of the waveguide core, resulting in an athermal design. Significant reduction of temperature dependence is expected to be achieved by using appropriate waveguide dimensions and adjusting the waveguide cross-section.

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