Low-Loss Grating-Coupled Silicon Ridge Waveguides and Ring Resonators for Optical Gain at Telecommunication Frequencies

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(Dated: October 17, 2009)

Low-loss grating-coupled ridge waveguides and ring resonators have been modeled and fabricated on silicon-on-insulator wafers. Theoretical models were developed and used to determine properties of the waveguides, and an optimized fabrication process has been employed to minimize loss. The resonators exhibit an intrinsic quality factor as high as $Q = 537,000$, corresponding to propagation loss of 1.23 dB/cm. We also discuss modal gain as a function of bulk gain for active materials integrated with waveguide structures. This represents a significant step towards a C-band emitting CMOS compatible light source.

Recent advances in the dense integration of silicon-based passive photonic components have highlighted the possibility of complex optical devices for computation, sensing, and telecommunications technology on the same chip as conventional CMOS electronics. Silicon-based devices exhibiting optical gain at frequencies below the silicon band gap would constitute critical components, but have yet to be demonstrated. The development of such a light source is hindered by the weak emission properties of suitable emitters, such as erbium-doped glass, in combination with relatively high propagation losses in silicon waveguide structures.\textsuperscript{3}

High index-contrast silicon-on-insulator (SOI) ridge waveguide structures can be fabricated on pre-existing CMOS fabrication lines and have been demonstrated with very low losses.\textsuperscript{6,7} We believe that quasi-planar light sources may be constructed by integrating ridge waveguide ring resonator structures with a suitable gain material. Using wafer bonding, the ridge waveguides can furthermore be combined into slot waveguide structures (Fig. 1) which are capable of drastically improving the properties of emitters in the narrow slot region through enhanced radiative emission, which may enable an efficient light source that can be pumped electrically through the silicon.\textsuperscript{1,2,3,4} As a gain material covering the ridge waveguides, we here consider erbium-doped yttria films. As gain material in the slot region of slot waveguides we consider erbium-doped silica glass.

In the following, we discuss the main loss mechanisms in high-index-contrast single-mode ridge waveguides as well as the modal gain as a function of the bulk active material gain. Furthermore, we demonstrate fabricated low-loss grating coupled ridge waveguides and ring resonators in SOI. Fig. 2 shows an optical microscope image of the fabricated structures.

Using single-crystalline silicon, the main source of propagation loss in the waveguides is due to roughness-induced scattering at the material boundaries. This loss can be shown to scale with the third power of the refractive index difference and therefore constitutes a major challenge in the design and fabrication of silicon waveguides.\textsuperscript{9}

In quasi-transverse-magnetic (TM) mode operation, losses also arise due to leakage of the guided TM-polarized mode into the transverse-electric (TE) mode supported by the silicon slab. This is due to mode conversion at the vertical ridge sidewalls creating quasi-TE polarized radiation of higher effective index than the slab TE mode. This loss cannot be reduced through optimized fabrication processes but has been shown to be drastically reduced for certain widths of the ridge, at which some of the leaking radiation interferes destructively. These “magic” widths, $W$, are, for single mode operation, given by equation Eq. (1) below:
Here, $\lambda$ represents the wavelength in free space, $n_{\text{TE},\text{core}}$ the effective fundamental guided TE mode index of a silicon slab with thickness equivalent to the thickness of the core of the ridge waveguide, and $n_{\text{TM},\text{guided}}$ the effective mode index of the fundamental guided quasi-TM mode supported by the ridge waveguide. The effective mode index of the quasi-TM mode is thus weakly dependent on the ridge width, such that an iterative scheme has to be employed to solve Eq. (1).

The guided mode indices are found using COMSOL Multiphysics, a commercially available finite-element mode solver, as well as an effective index method. The effective index method reduces the ridge waveguide geometry into an analytically solvable one-dimensional three-layer slab waveguide problem by assuming the core and slab regions of the waveguide to be of continuous refractive index. This equivalent index profile identical to the index distribution in the core or slab region.

The third major loss mechanism is bending loss in the ridge resonator structures. This loss mechanism also exists independent of fabrication-induced defects and will vary over many orders of magnitude depending on the cross-section and bending radius of the waveguides. Using the effective index method and diffraction theory, the bending loss coefficient, $\alpha$, can be approximated as:

$$\alpha = \frac{\kappa^2 \gamma^2 e^{\gamma W}}{\beta (1 + \gamma \frac{W}{2}) (\kappa^2 + \gamma^2)} \exp \left( -\frac{2\gamma^3}{3\beta^2} R \right)$$

where $\kappa$ and $\gamma$ are defined as:

$$\kappa = \sqrt{n_{\text{eff,core}} k_0^2 - \beta^2}$$

$$\gamma = \sqrt{\beta^2 - n_{\text{eff,slab}}^2 k_0^2} ,$$

and $k_0$ is the free space wavelength, $\beta$ is the propagation constant of the guided mode, and $R$ is the bending radius of the waveguides. Furthermore, $n_{\text{eff,core}}$ and $n_{\text{eff,slab}}$ represent the effective index of the core region and slab region respectively. $W$ represents the width of the ridge. Figure 3 shows the bending loss of the fundamental guided TE and TM modes supported by a ridge waveguide in 220 nm SOI as a function of normalized slab thickness.

The bending loss becomes quickly negligible for both guided TE and TM modes as the ridge height increases. Narrow ridges can however help reduce scattering loss as they reduce the modal overlap with the material boundaries.

The other defining factor is the interaction of a guided mode with the active layer. The modal gain coefficient $\alpha_{\text{mode}}$ of a mode supported by the structure is related to the bulk material gain coefficient $\alpha_{\text{bulk}}$ of the active material by the confinement factor, $\Gamma$, which is given by:

$$\Gamma = \frac{\alpha_{\text{mode}}}{\alpha_{\text{bulk}}}$$

where $n_A$ is the refractive index of the gain material and the surface integral in the denominator is over the area $A$ in which the gain material is located. Eq. (6) shows that the modal gain scales with the electric field in the active region in relation to the total power flow. These field quantities can be determined using COMSOL Multiphysics. Fig. 4 shows representative solutions for a ridge waveguide covered in erbium-doped yttria and a slot waveguide with erbium-doped glass in the slot region. The refractive index of yttria is taken to be 1.9.

Fig. 5 depicts simulation results for the confinement factors of the fundamental guided TE and TM modes in
yttria-clad ridge waveguides as a function of upper slab and cladding thickness. As high-quality erbium-doped yttria films are fabricated using atomic layer deposition, only thin films are practical, such that we limited the domain to a maximum cladding thicknesses of 200 nm. The sparse local minima in the density plots corresponding to the TM-polarized modes are due to non-convergence of the finite-element solver which plagued certain waveguide geometries. The general trends in these plots reflect well-converged solutions and are thus believed by the authors to be an accurate representation of the physical modes. The data suggest an optimal slab thickness for the ridge waveguides depending on the thickness of the yttria cladding. In TE-mode operation, the ideal silicon slab thickness is on the order of a few nanometers, however in TM-mode operation around 150 nm. Accordingly, efficient devices will have to be designed specifically for TE- or TM-mode operation. Peak confinement factors of 50% and 60% were achieved for TE and TM polarizations, respectively. As waveguides designed to operate in TE mode are not required to match the magic width criterion, the ridge width represents another parameter to be optimized.

Fig. 6 shows the confinement factors of the fundamental quasi-TM modes of a slot waveguide with erbium-doped glass in the slot layer. The increase of the confinement factor with the slot width indicates that the strong enhancement of the electric field in the slot layer is outweighed by the relatively smaller area over which the numerator in Eq. (6) is integrated. However, it is desirable to have slots as thin as possible with respect to the exhibited gain in order to be able to pump the active material electrically, which would represent a great advantage over optical pumping as no auxiliary pump light source is required. Furthermore, the strong electric field in the slot region of TM-polarized slot modes enhances the efficiency of the gain material. The slot waveguide modes can be described as the coupled modes of two closely spaced silicon slab waveguides. For a core thickness of 220 nm, these modes will decouple for slot thicknesses greater than about 80 nm. The simulations show, however, that the confinement factor for TM-polarized slot modes can well surpass 40%.

Some of the lowest loss ridge waveguides have been formed by anisotropic reactive ion etching and selective oxidation. While both methods yield smooth side-walls, the oxidation will additionally passivate the silicon which further reduces loss. To fabricate our waveguides, negative electron beam resist is first patterned on 220 nm SOI using the electron pattern generator of the Kavli Nanoscience Institute (KNI). The structures are then formed using a C₄F₈/O₂ etch in the KNI’s inductively coupled reactive ion etching chamber. The samples are then cleaned in O₂ plasma to remove remaining polymer from the surface. Finally, an oxide passivation layer is grown using dry oxidation. Fig. 7 shows SEM and AFM micrographs of a waveguide, revealing a mean square surface roughness below 1.8 nm.
FIG. 6: Confinement factor of the fundamental quasi-TM mode of a slot waveguide with silica glass in the slot layer as a function of upper slab and slot thickness. The ridge height is 40 nm and the ridge width is 700 nm.

The fabricated waveguides have a ridge height of 30 nm and a ridge width of 720 nm. The ring resonators have a diameter of 400 μm and are separated from the waveguides by a coupling gap of 1 μm. The gratings are optimized for operation at 1550 nm.

Light from a New Focus 6428 Vidia Swept tunable diode laser is coupled into the structures using a lensed fiber focuser with an estimated working distance of 12.4 mm and a spot size of 8 μm. The TE and TM modes are selectively addressed by adjusting the angle of incidence of the light onto the gratings. The laser is then set to sweep over wavelengths around 1550 nm at a constant speed of 1 nm/s. The outgoing light is picked up using an identical lensed fiber focuser aimed at the through- or drop port and measured using a InGaAs photoreceiver. The drop port intensities transmitted in quasi-TE and TM modes as a function of input wavelength are shown in Fig. 8. They show a clear intensity drop off at the ring resonator resonances. The resonances are spaced 0.508 nm apart in TE- and 0.516 nm in TM-like mode operation. From this free spectral range the group indices of the guided TE and TM resonator modes can be extracted as 3.76 and 3.66, respectively. The linewidth of the resonators in TE-mode operation is 8.65 pm and in TM mode operation 26.5 pm. This corresponds to propagation losses of 1.23 dB/cm and 3.71 dB/cm respectively. The loaded quality factor Q is then 179,000 for TE and 58,000 for TM. As there are identical through- and drop port couplers, the intrinsic Qs of the resonators are then 537,000 and 174,000, as given by the equation:

\[
\frac{1}{Q_{\text{loaded}}} = \frac{1}{Q_{\text{intrinsic}}} + \frac{2}{Q_{\text{coupler}}} = \frac{3}{Q_{\text{intrinsic}}} \quad (7)
\]

where \(Q_{\text{intrinsic}} = Q_{\text{coupler}}\) for a critically coupled resonator. The 15dB extinction at resonance in TE-mode operation justifies the assumption of critical coupling, but the assumption is more dubious for TM-mode operation. The signal in TM-mode operation is overall noisier, because the gratings work less efficiently for this polarization.

Conclusively, considering the high possible confinement factors and assuming no significant further loss in the gain materials, light emitting devices based on the fabricated ridge waveguide devices should be possible. The demonstrated theoretical methods can be used to optimize the design of such structures.

Acknowledgments

The authors gratefully acknowledge the rest of the Atwater group at Caltech as well as the KNI staff for their help. J. P. B. Müller thanks the Caltech - University of Iceland Exchange Program as well as the Kavli Nanoscience Institute for his undergraduate research fellowships. J. P. B. Müller thanks his co-mentor R. M. Briggs and his mentor H. A. Atwater for a fantastic summer in California!
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