Horizontal single and multiple slot waveguides: optical transmission at λ = 1550 nm

Rong Sun[1]*, Po Dong[2]*, Ning-ning Feng[1], Ching-yin Hong[1], Jurgen Michel[1], Michal Lipson[2], Lionel Kimerling[1]

1Department of Materials Science and Engineering, Massachusetts Institute of Technology
77 Massachusetts Avenue, Cambridge, Massachusetts 02139
2School of Electrical and Computer Engineering, Cornell University
411 Phillips Hall, Ithaca, NY 14853
** Co-first authors*
Corresponding author: rsun@mit.edu

Abstract: We experimentally demonstrate the optical transmission at 1550 nm of the fundamental slot modes (quasi-TM modes) in horizontal single and multiple slot waveguides and ring resonators consisting of deposited amorphous silicon and silicon dioxide. We demonstrate that the horizontal multiple slot configuration provides enhanced optical confinement in low index slot regions compared to a horizontal single slot structure with the same total SiO_2 layer thickness by comparing their thermo-optic coefficients for the horizontal slot ring resonators. We show in these early structures that horizontal slot waveguides have low propagation loss of 6 ~ 7 dB/cm. The waveguide loss is mainly due to a-Si material absorption. The addition of a-Si/SiO_2 interfaces does not introduce significant scattering loss in a horizontal multiple slot waveguide compared to a horizontal single slot waveguide.

OCIS codes: (130.2790) Guided waves; (130.3120) Integrated optics devices; (230.7380) Waveguides, channeled; (240.5770) Roughness; (160.6840) Thermo-optical materials

References and links

1. T. Baehr-Jones, M. Hochberg, G. Wang, R. Lawson, Y. Liao, P. A. Sullivan, L. Dalton, A. K.-Y. Jen, A. Scherer, "Optical modulation and detection in slotted Silicon waveguides," Opt. Express **13**, 5216 (2005)
2. C. A. Barrios, M. Lipson, "Electrically driven silicon resonant light emitting device based on slot-waveguide," Opt. Express **13**, 10092 (2005)
3. T. Fujisawa, M. Koshiba, "Guided Modes of Nonlinear Slot Waveguides," IEEE Photon. Technol. Lett. **8**, 1530 (2006)
4. P. Andrew Anderson, Bradley S. Schmidt and Michal Lipson, "High confinement in silicon slot waveguides with sharp bends," Opt. Express **14** 9197 (2006)
5. Q. Xu, V. R. Almeida, R. R. Panepucci, and M. Lipson, "Experimental demonstration of guiding and confining light in nanometer-size low-refractive-index material," Opt. Lett. **29**, 1626 (2004)
6. N. N. Feng, J. Michel, and L C. Kimerling, "Optical field concentration in low-index waveguides," IEEE J. Quantum Electron. **42**, (2006)
7. T. Baehr-Jones, M. Hochberg, C. Walker, and A. Scherer, "High-Q optical resonators in silicon-on-insulator-based slot waveguides," Appl. Phys. Lett. **86**, 081101 (2005)
8. P. Karminow, L. W Stulz, "Loss in cleaved Ti-diffused $LiNbO_3$ waveguides," Appl. Phys. Lett. **33**, 62 (1978)
9. L.A. Eldada, "Polymer integrated optics: promise versus practicality," Proceedings of SPIE **4642**, Organic Photonic Materials and Devices IV, 11 (2002)

#89376 - $15.00 USD Received 6 Nov 2007; revised 11 Dec 2007; accepted 12 Dec 2007; published 17 Dec 2007

1. Introduction

Slot waveguides are a newly developed class of waveguides that has received significant attention and promise many applications in recent years [1-4]. A slot waveguide consists of at least one narrow low index region sandwiched between high index regions. Because of the field discontinuity at the high index contrast interfaces, the optical field is strongly enhanced in the low index region nears the interfaces [5,6]. However, high intensity of the optical field at the interface results in high waveguide scattering loss due to interface roughness. A vertical slot fabrication involves etching in a very narrow region which can cause large roughness in the vertical interfaces. The best reported loss for the quasi-TE mode in a vertical slot waveguide with a single slot of 50 nm or less is greater than 11.6 ± 3.6 dB/cm [7]. A horizontal slot structure featured with a horizontal low index slot can be fabricated by layered deposition or thermal oxidation. The corresponding slot waveguide devices have virtually no fabrication constraints on slot thickness and can have very low scattering loss due to small surface or interface roughness for the fundamental slot mode, the quasi-TM mode. We have also previously proposed multiple slot configurations in a horizontal slot waveguide to provide enhanced optical confinement in the low index slot region [6].

In this paper, we experimentally demonstrate the low loss optical transmission at 1550 nm of the fundamental slot modes in horizontal single and multiple slot waveguides consisting of deposited amorphous silicon and silicon dioxide. The propagation loss is measured as 6.3 ± 0.2 dB/cm and 7.0 ± 0.2 dB/cm for single and multiple slot waveguides, respectively. We also demonstrated that horizontal multiple slot waveguides provide enhanced optical confinement in the low index slot regions compared to that in horizontal single slot waveguides with the same SiO_2 layer thickness. The enhancement is demonstrated directly by comparing the thermo-optic coefficients in horizontal single and triple slot ring resonators. Unless otherwise specified, all slot waveguides in the following context are horizontal slot waveguides and only the quasi-TM mode properties are discussed.

2. Experimental

The single and triple slot waveguides are made of amorphous silicon (a-Si, n = 3.5) and silicon dioxide (SiO_2, n = 1.46). On a 3 **μ**m thermal oxide silicon wafer, we deposit amorphous silicon and silicon dioxide using Plasma Enhanced Chemical Vapor Deposition (PECVD). To show differences in waveguide properties resulting solely from single slot or multiple slot configuration, we designed waveguide geometries such that the overall waveguide height, total a-Si layer thickness, and total SiO_2 layer thickness are approximately the same for both single and triple slot waveguides. For the fabricated single slot waveguide, the stack has two 223 nm a-Si layers and one 55 nm SiO_2 layer. For the fabricated triple slot waveguide, the stack consists of two 152 nm a-Si outer layers, two 56 nm a-Si inner layers, and three 17 nm SiO_2 slot layers. All waveguides and ring resonators are 500 nm wide, patterned by E-Beam Lithography (EBL), and Reactive Ion Etch (RIE). No post-etch waveguide smoothing has been applied on these very early structures. Finally, 3 μm PECVD SiO_2 is deposited as the top cladding layer. The schematic structures as well as their normalized optical field ($|E|^2$) distributions are shown in Fig. 1(a1, b1). The absolute value for the E field can be calculated with Poynting vector, $<S> \sim \varepsilon_o cn|E|^2/2$, where $<S>$ is the time-averaged energy flux, ε_o is the permittivity of free space, c is the free space speed of light, n is the refractive index, and E is the electric field. For example, for 1 mW transmitted optical power in our triple slot waveguides, the maximum E field in SiO_2 slot regions is about 2.5×10^8 V/m, one order of magnitude larger than in the Si regions. All the simulations were carried out using a numerical model solver based on finite-difference time-domain (FDTD) methods. The corresponding Scanning Electron Microscope (SEM) images of the cross sections of the layered structures are also shown. The deposited layered structures and each layer thickness are well controlled.

#89376 - $15.00 USD Received 6 Nov 2007; revised 11 Dec 2007; accepted 12 Dec 2007; published 17 Dec 2007

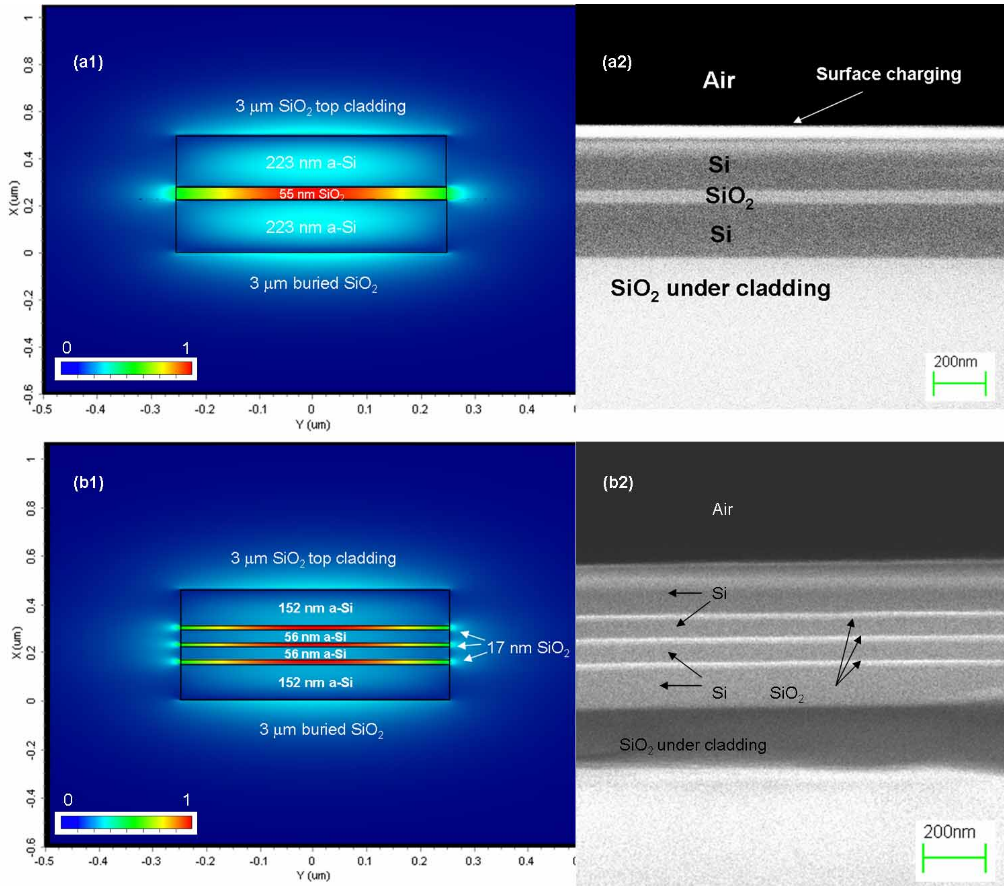

Fig. 1. Schematic representation of the structures of a single (a1) and a triple slot waveguide (b1). The normalized optical field ($|E|^2$) distributions are simulated using a numerical mode solver based on finite-difference time-domain (FDTD) methods. Their corresponding cross-sectional SEM images to the right of the schematic drawings (a2) and (b2) show that the layered structures and each layer thickness are well controlled in fabrication.

3. Results and discussion

We measured waveguide propagation loss using the cut-back method [8]. As shown in Fig. 2, at 1550 nm for the quasi-TM modes, the waveguide losses for single and triple slot waveguides are measured to be 6.3 ± 0.2 dB/cm and 7.0 ± 0.20 dB/cm, respectively. The relatively small difference in waveguide loss demonstrates that the addition of a-Si/SiO_2 interfaces in triple slot waveguides does not introduce significant scattering loss under the same process conditions as the single slot waveguides. The horizontal single slot waveguide loss is much lower than that in a vertical slot waveguide with slot width of 50 nm (~11.6 ± 3.5 dB/cm) [7]. The excellent low loss performance for the quasi-TM modes of horizontal slot waveguides are due to (1) the fact that the TM mode is relatively insensitive to waveguide sidewall roughness; and (2) low surface roughness for deposited films. For both deposited a-Si and SiO_2 layers, the surface roughness is less than 5 Å as measured by Atomic Force Microscopy (AFM). The dominant loss source in our a-Si/SiO_2 waveguide devices is the a-Si bulk absorption.

#89376 - $15.00 USD Received 6 Nov 2007; revised 11 Dec 2007; accepted 12 Dec 2007; published 17 Dec 2007

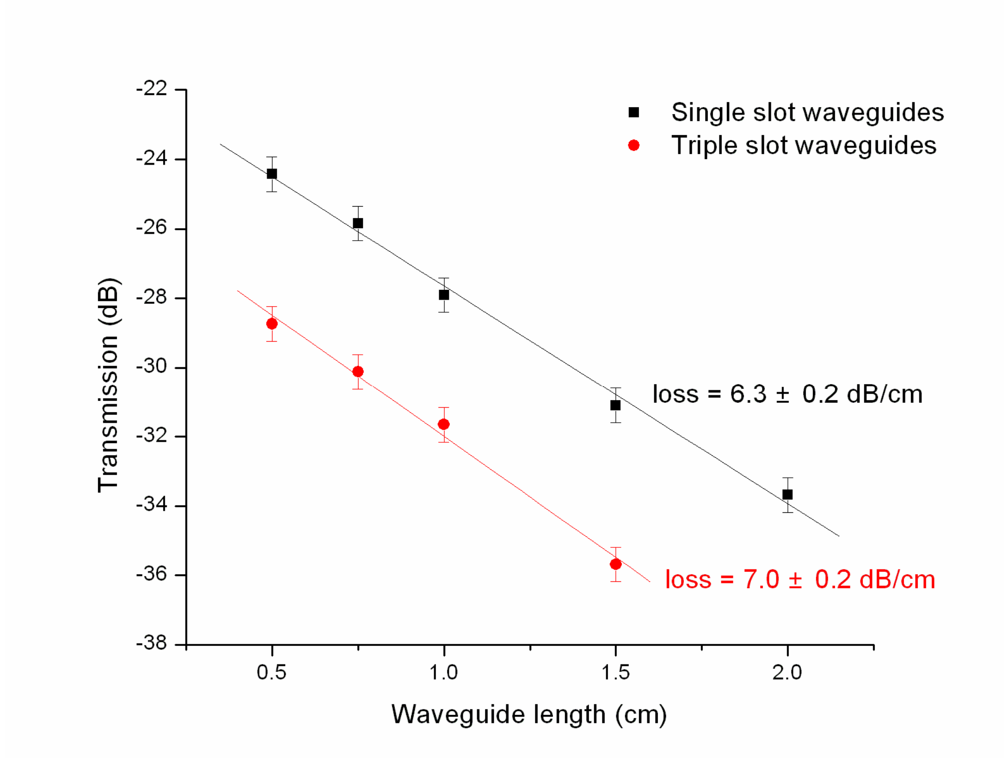

Fig. 2. Single and triple slot waveguide losses: waveguide total insertion loss (dB) versus waveguide length (cm). The slope of the linear fit represents the waveguide propagation loss in dB/cm. The lines are corresponding to linear fits, serving the purpose to guide the eyes.

The optical confinement factors in the SiO_2 slots, defined as the ratio of the optical power in the SiO_2 slot(s) and the total optical power, are calculated to be 36% and 56% for the single and triple slot waveguides, respectively. The confinement factors can be verified directly by measuring the thermo-optic coefficients of the slot ring resonator devices. For a silicon or SiO_2 waveguide, the refractive index increases as temperature increases, causing the ring resonator's resonant wavelengths to shift to longer wavelength. But because the thermo-optic effect in SiO_2 is about ten times weaker than that in a-Si [9], the overall thermo-optic coefficient in an a-Si/SiO_2 slot waveguide is expected to be much smaller than in a regular a-Si waveguide with similar dimensions due to the high optical confinement in the SiO_2 slot region(s).

The fabricated single and triple slot ring resonators have the same ring-bus gaps of 250 nm and the same ring radii (R) of 10 μm. Figure 3(a) shows their spectra between 1535 nm and 1555 nm. Their free spectral ranges (FSR) and group indices (n_g) around 1550 nm are summarized in Tab. 1. The corresponding simulation results are included for comparison. Their theoretical values were calculated using Eq. (1) and (2). The effective indices (n_{eff}) used in calculations were simulated directly using the mode solver. The on-resonance extinction is about 15 dB. Figure 3(b) shows the Lorentzian fitting on one of the resonance of the triple slot ring resonator. The -3dB bandwidth is 0.119 ± 0.008 nm. According to Eq. (3), this corresponds to a quality factor (Q) of 13000 ± 1000 at around 1550 nm. The low Q factor is due to non-critical coupling conditions. Over all, the quality factors for single and triple slot ring resonators are estimated to be around 12500 ± 2500.

$$n_g = n_{eff}(\lambda) - \lambda \frac{dn_{eff}(\lambda)}{d\lambda} \quad (1)$$

#89376 - $15.00 USD Received 6 Nov 2007; revised 11 Dec 2007; accepted 12 Dec 2007; published 17 Dec 2007

$$FSR = \lambda_{m+1} - \lambda_m \approx \frac{\lambda^2}{n_g(\lambda) \cdot 2\pi R} \tag{2}$$

$$Q = \frac{\lambda}{\Delta\lambda_{-3dB}} \tag{3}$$

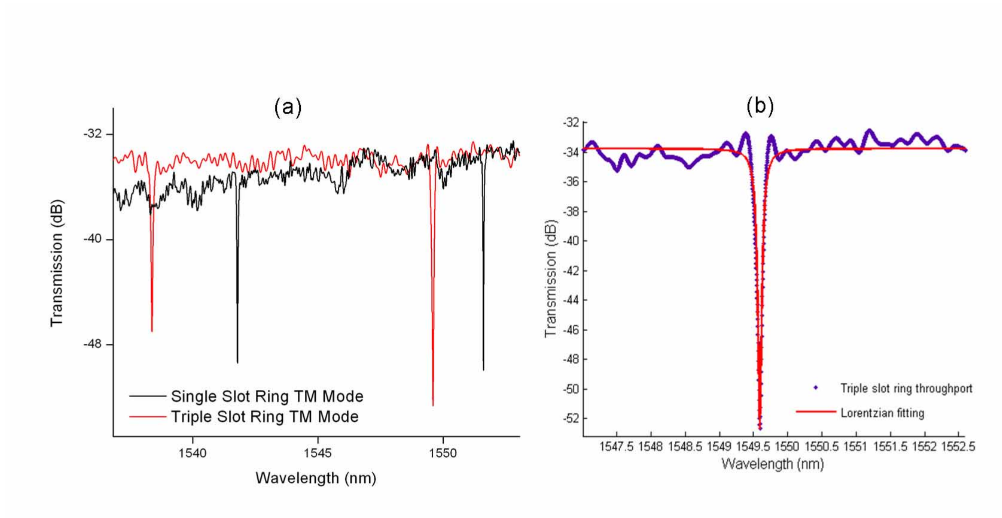

Fig. 3. (a) Ring resonator spectra of a single and a triple slot waveguide. Both ring radii are 10 μm and bus-ring gaps are 250 nm; and (b) the Lorentzian fitting on triple slot ring resonator.

Tab. 1. Summary of the measured and simulated FSR and group index around 1550 nm of the single and triple slot ring resonators with 10 μm radius.

	FSR		Group Index	
	Measured	Simulation	Measured	Simulation
Single Slot	9.8	9.4	3.902	4.055
Triple Slot	11.2	12.2	3.401	3.139

Figure 4 shows the thermo-optic coefficient measurement results of a single and a triple slot ring resonator. The tunable laser we used in experiments has a resolution of 2.5 pm. The measurement errors on the resonance wavelengths are minimal. The measured thermo-optic coefficient of the triple slot waveguide is 65.4 pm/^{o}C, which is 12% lower than that of the single slot ring resonator, 74.6 pm/^{o}C; their simulated thermo-optic coefficients are 64.6 pm/^{o}C and 76.8 pm/^{o}C, respectively, which correlates well with the measurement results. The difference in thermo-optic coefficient is due to the enhanced confinement in the low index SiO_2 slot region in the triple slot ring resonator. For comparison, the thermo-optic coefficients for the fundamental TM mode in a 500 nm tall, 500 nm wide, a-Si channel ring resonator is calculated to be 102.7 pm/^{o}C. The overall low thermo-optic coefficients for the slot ring resonators confirm the optical concentration in low index SiO_2 slot region(s) in our slot waveguides devices. The lower thermo-optic coefficient in the triple slot ring resonator directly proves that multiple slot configuration provides greater optical confinement in low index slots compared to the single slot configuration.

#89376 - $15.00 USD Received 6 Nov 2007; revised 11 Dec 2007; accepted 12 Dec 2007; published 17 Dec 2007

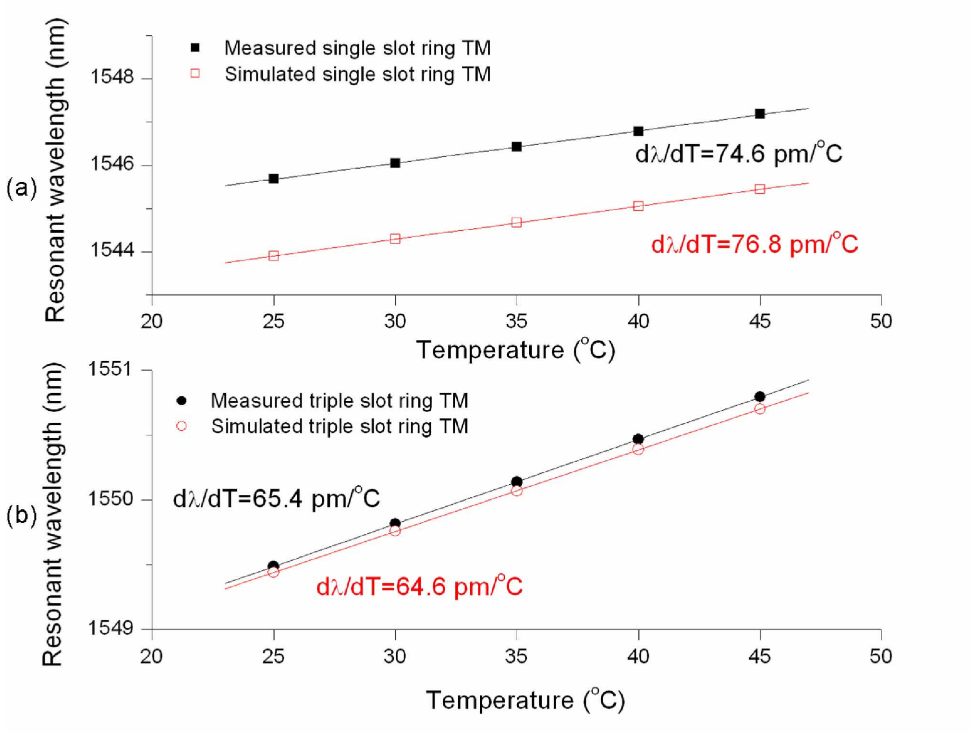

Fig. 4. The measured and simulated thermo-optic coefficients for the quasi-TM modes of a single (a) and a triple (b) slot ring resonator. The simulations match well with the experimental results. The thermo-optic coefficient of the triple slot ring resonator is lower than that of the single slot ring resonator due to the improved confinement in the slot region. The difference between simulation and measurement is possibly due to ring radius and layer thickness variation.

4. Conclusions

We have experimentally demonstrated optical transmission in horizontal a-Si/SiO_2 single and multiple slot waveguides and ring resonator devices. Low propagation loss has been achieved in these early devices. The thermo-optic coefficient measurements verify that the multiple slot configuration can further enhance optical confinement in the low index slot regions. With the low propagation loss for the fundamental slot mode and enhanced optical confinement realized in low index slot regions, horizontal slot waveguides with multiple slot configurations are very promising for applications such as dielectric gain media and non-linear optics.

Acknowledgements

This work was sponsored by the Si-based Laser Initiative of the Multidisciplinary University Research Initiative (MURI) under the Air Force Aerospace Research OSR award number FA9550-06-1-0470 and supervised by LTC Gernot Pomrenke.. The authors would like to thank the Microsystem Technology Laboratory, Center for Materials Science and Engineering at MIT, and Center for Nanofabrication Facilities at Cornell University for providing fabrication facilities. The authors would also like to thank Dr. Anuradha Agarwal for useful discussions and Juejun Hu for experimental support.

#89376 - $15.00 USD Received 6 Nov 2007; revised 11 Dec 2007; accepted 12 Dec 2007; published 17 Dec 2007