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Ultralow-Loss Silicon Ring Resonators

Aleksandr Biberman,[1] Michael J. Shaw,[2] Erman Timurdogan,[1] Jeremy B. Wright,[2] and Michael R. Watts[1,*]
[1]*Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA*
[2]*Sandia National Laboratories, P.O. Box 5800, Albuquerque, New Mexico 87185, USA*
[*]*Corresponding author: mwatts@mit.edu*

***Abstract*—We experimentally demonstrate silicon ring resonators with internal quality factors of $Q_0=2.2\times10^7$, corresponding to record 2.7-dB/m losses. We show that the losses are bend-loss-limited, indicating that the loss limit for silicon has not been reached.**

I. INTRODUCTION

Waveguide loss is a critical parameter for many important microphotonic devices and systems, such as high-quality filters, delay lines, high fidelity sensor systems [1], as well as systems addressing many key challenges in computing and communication [2]. Additionally, silicon is quickly proving to be the waveguide material of choice for microphotonics, enabling active componentry such as modulators, switches, and detectors [3–5]; passive components such as microring resonators, polarization-transparent devices, and compact polarization splitters and rotators [6–8]; as well as fascinating nonlinear devices such as comb generators, wavelength converters, and time lenses [9,10]. However, the limit of propagation losses within silicon remains as part of ongoing research, and is yet to be determined.

Silicon propagation losses using strip, locally-oxidized, and rib waveguides have achieved 80 [12], 21 [13], and about 20 dB/m [14–16], respectively. Silicon microdisk resonators have been shown to have propagation losses as low as 10 dB/m, with quality factors of $Q=5\times10^6$, limited by absorption in surface states [16]. In this work, we apply techniques of reflowing photoresist [16], and oxidation-based smoothing, to a ridge waveguide [11,12]. The ridge waveguide substantially reduces sidewall interaction with the fundamental TE and TM modes (Figure 1c), enabling experimentally-measured quality factors as high as 2.2×10^7, corresponding to record-low propagation losses of 2.7 dB/m in silicon, a factor of five lower than in [16]. Moreover, by comparing the measured transverse electric (TE) and transverse magnetic (TM) resonances to numerical results obtained by a full-vectorial cylindrical modesolver, we demonstrate that the quality factors are limited by the incomplete confinement of the ridge waveguide, and the resulting bend-induced radiation, rather than fabrication

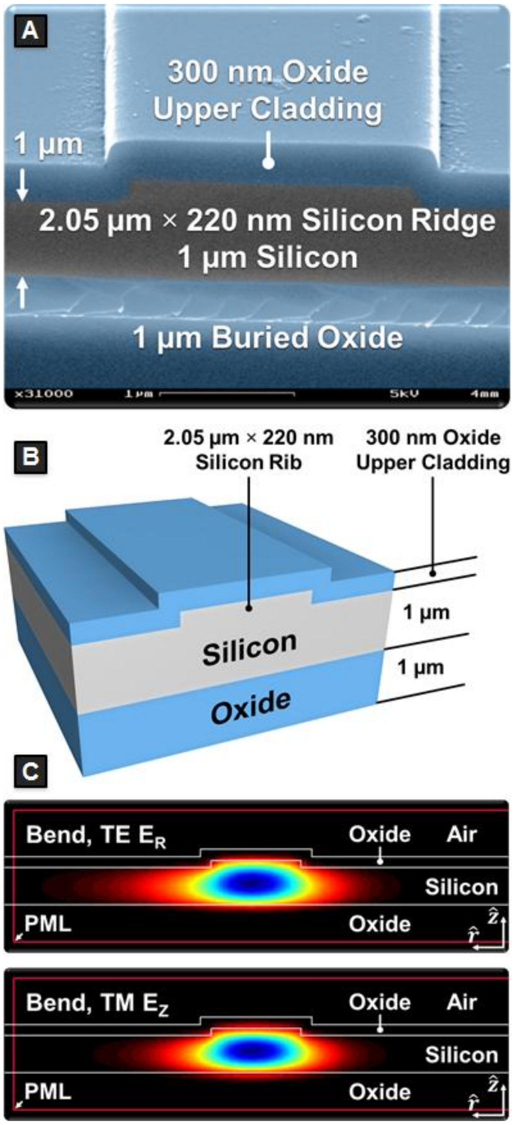

Figure 1. (a) Scanning-electron-microscope image of the silicon photonic waveguide overlaid with false coloring. (b) Representation of its layers and dimensions. (c) Modesolver simulations of the TE and TM modes at 1600 and 1554 nm, respectively. The bend-loss-limited Q's from the modesolver simulations closely match the simulated results for both the TE and TM modes, indicating that the measured Q's are limited by bend-loss-induced radiation.

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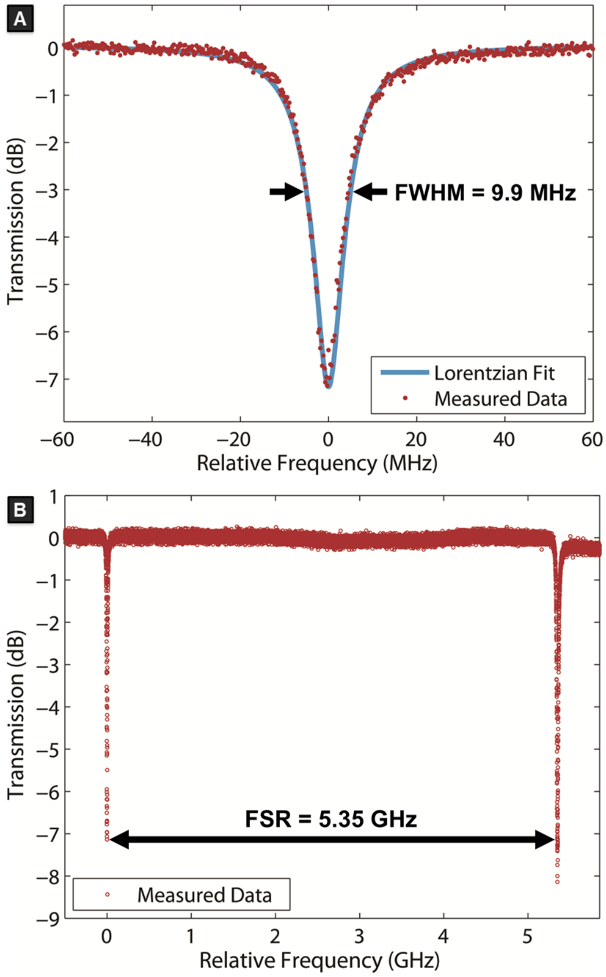

Figure 2. Experimentally-measured TE spectral responses of the silicon photonic ring resonator. (a) Single passband, showing the full width at half maximum, with a corresponding Lorentzian fit. (b) Two consecutive passbands, showing the free spectral range.

or material-induced loss. Thus, we conclude that even lower losses are possible.

II. Fabrication and Experimentation

A silicon ridge waveguide design was chosen to demonstrate low-loss waveguides with the assumption that reducing the sidewall interaction, with proper fabrication, could enable ultralow propagation losses. The waveguides were fabricated from a silicon-on-insulator (SOI) wafer, with a 3.26-µm-thick silicon layer and a 1-µm-thick oxide layer. The silicon layer was thinned to 1.33 µm by oxidizing the wafer surface in a steam oxidation process followed by an oxide strip. A 200-nm-thick ridge was patterned and etched to a silicon thickness of 1.13 µm everywhere except the ridge; the total thickness of the ridge is 1.33 µm. Finally, a 300-nm-thick thermal oxide layer was grown, consuming 0.13 µm of silicon, and leaving behind a 200-nm-thick ridge waveguide on a 1-µm-thick silicon slab. While patterning the ridge, a reflowed photoresist strategy was utilized [16], where the photoresist was patterned and heated for a very short time. The top oxidation process and reflowed photoresist reduce or eliminate sidewall asperities created from the ridge etching process. A scanning-electron-microscope (SEM) image of the final waveguide is shown in Figure 1a. The resulting ridge was measured to be 2.05-µm wide and 220-nm tall, on a 1-µm slab (Figure 1b).

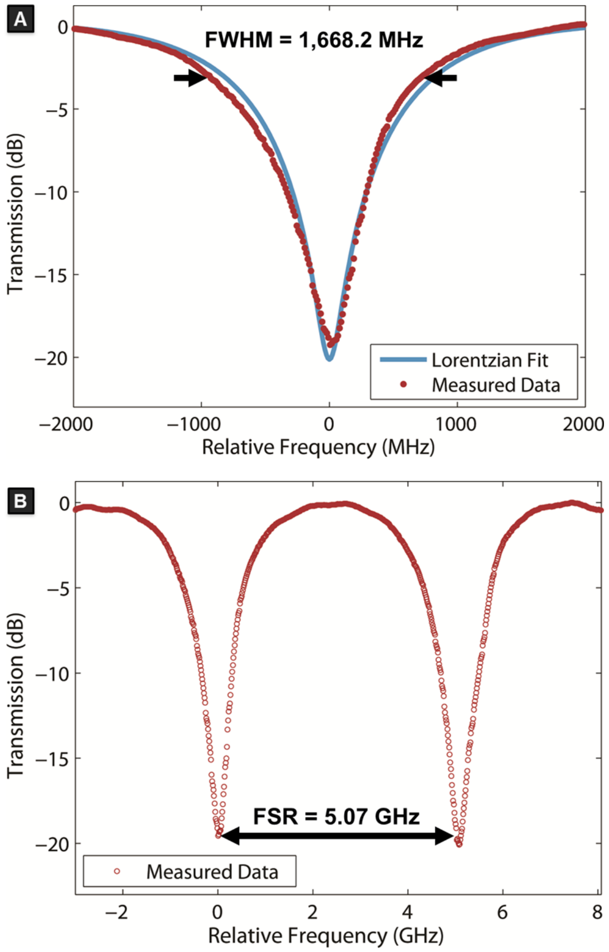

Figure 3. Experimentally-measured TM spectral responses of the silicon photonic ring resonator. (a) Single passband, showing the full width at half maximum, with a corresponding Lorentzian fit. (b) Two consecutive passbands, showing the free spectral range.

The device in our experiments comprises the aforementioned silicon photonic waveguide coupled to a ring resonator with a radius of 2.45 mm. Because the TE resonances of these ring resonators are so narrow, on the order of ten megahertz, accurate measurements of their response required careful instrumentation. To measure the TE resonances, we continually swept a tunable laser source with a 100-kHz linewidth over a 7 GHz range, to span two consecutive resonances, or one free spectral range (FSR). As we swept the tunable laser source across the resonances, we obtained the spectrally-correlated transmission in the time domain on an oscilloscope. Correlating the temporal duration between consecutive resonances to the FSR of the ring separately measured by stepping the tunable laser, we obtained calibrated curves for the TE spectral responses of the ring resonator. For the TE resonance at 1600 nm, we measure a resonance width of 9.9 MHz, shown in Figure 2. Fitting the data to a transfer matrix model of the Lorentzian resonance, we obtain an internal quality factor of $Q_0=2.2\times10^7$, and from a Taylor series expansion of the complex propagation constant ($\beta_c=\beta_r-j\alpha$), we have $\alpha=\omega/(2Q_0v_g)$, resulting in $\alpha_{TE\text{-}0}=3.1\times10^{-3}$ cm^{-1} for the imaginary component of the complex propagation constant. This corresponds to a propagation loss of 2.7 dB/m, a record for silicon waveguides. Additionally, we measure the spectral response of the TM mode centered at 1554 nm, shown in Figure 3. Here, we find the internal quality factor to be $Q_0=1.4\times10^5$ from the fit, and calculate $\alpha_{TM\text{-}0}=0.5$ cm^{-1}.

Inserting the dimensions of the ridge waveguide obtained from profilometry and SEM data, and refractive indices of 3.48 for silicon and 1.445 for silicon dioxide, we obtained the TE and TM fundamental modes and complex propagation constant of the structure. For this, we used a full-vectorial cylindrical modesolver and perfectly matched layers (PML) depicted in Figure 1c. For the TE mode at 1600 nm, we obtain $Q_0=2.2298\times10^7$ and $\alpha_{TE\text{-}0}=3.1034\times10^{-3}$ cm^{-1}. For the TM mode, we obtain $Q_0=1.3246\times10^5$ and $\alpha_{TM\text{-}0}=0.5408$ cm^{-1}. The Q's found from simulation are consistent with our measured data. Therefore, our ring losses are limited by the radiation losses inherent to the realized structure, and not due to fabrication or other material limitations such as free-carrier absorption (FCA), surface-state absorption (SSA) and scattering, two-photon absorption (TPA), and defects. Thus, even higher quality factors for more compact devices are achievable by shrinking the ridge height or widening the ridge width of the waveguide.

III. CONCLUSIONS

We experimentally demonstrate a new record for ultralow-loss silicon, at 2.7 dB/m, achieving ring resonators with internal quality factors of 2.2×10^7, a factor of five better than what has previously been shown. We confirm our results by simulating these structures using a full-vectorial cylindrical modesolver, showing that the major limitation in the quality factor in our rings arises from the limited confinement factor of the ridge waveguide. With greater modal confinement, which can be readily achieved, we expect to achieve even lower propagation loss for even more compact resonators. The impact of such low loss in silicon waveguides will no doubt extend from communications and sensing applications to delay lines and nonlinear optical effects. Future efforts will focus on replicating such losses in highly confined waveguides.

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