Ultra-High-Q Racetrack on Thick SOI Platform through Hydrogen Annealing

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Abstract *We experimentally demonstrate a racetrack resonator consisting of rib waveguides and strip-waveguide-based Euler bends on thick SOI platform, with an intrinsic quality factor of 14 million, corresponding to a propagation loss of 2.7 dB/m. This result was achieved through sidewall roughness smoothing using hydrogen annealing. ©2022 The Author(s)*

Introduction

Microresonators are important structures in photonic integrated systems thanks to their filtering and energy storing and enhancing capabilities, finding applications in optical frequency comb generation [1], microwave photonics [2], narrow linewidth lasers [3] and, more recently, quantum photonics [4]. One important parameter of microresonators is the quality (Q-) factor, which relates to the resonance linewidth. There have been many efforts to achieve record high Q-factors, particularly exploiting silicon-on-insulator (SOI) technology [5,6], however for the case of racetrack resonators, the demonstrated Q-factors have not surpassed 10 M in SOI yet.

The relation between propagation losses and the intrinsic Q-factor of a resonator is inverse, the lower the losses the higher the Q. In most integrated photonics platforms, the propagation losses are limited by the scattering induced by the interaction of the mode with the sidewall roughness. This interaction is particularly strong in sub-micron scale SOI platforms. In the case of VTT's 3 µm thick SOI platform, the field is highly confined inside the core, thanks to the large size of the waveguides, hence it is possible to achieve very low propagation losses (~0.1 dB/cm) in a broad wavelength range (1.2-4 µm) [7]. We have already exploited this feature to show intrinsic Qs of 8 M for a ring resonator based on rib waveguides and 4.3 M for a racetrack based on the combination of rib and strip waveguides [8].

The advantage of the rib waveguide based ring resonator is that these waveguides have lower propagation losses, therefore can provide higher Qs, however they have high bending losses, so a large footprint is required, whereas racetracks can be more compact, thanks to the use of strip waveguides to obtain a tighter bending radius. In this work we experimentally demonstrate an intrinsic Q of 14 × 10^6 for a racetrack, which is higher than the Q previously achieved in our platform for a larger ring resonator [8], and it is the highest for a racetrack resonator on SOI platform, to the best of our knowledge. We achieved this result by reducing the propagation losses of our waveguides through sidewall roughness smoothing by hydrogen annealing. This process is completely compatible with the current fabrication methods at VTT, hence it can be integrated into the process flow and offered in multi-project wafer runs in the future, opening the door to new applications that could benefit from the demonstrated ultra-low losses.

Design

A schematic of the designed racetrack is shown in Fig. 1(a). The straight and coupling sections consist of rib waveguides, characterized by a width of 3 µm and etch depth of 1.2 µm. These dimensions guarantee a single-mode operation over an ultra-broad wavelength range (1.2-4 µm), along with ultra-low propagation loss, thanks to the field being so well confined inside the core of the waveguide [7]. Since it is not possible to

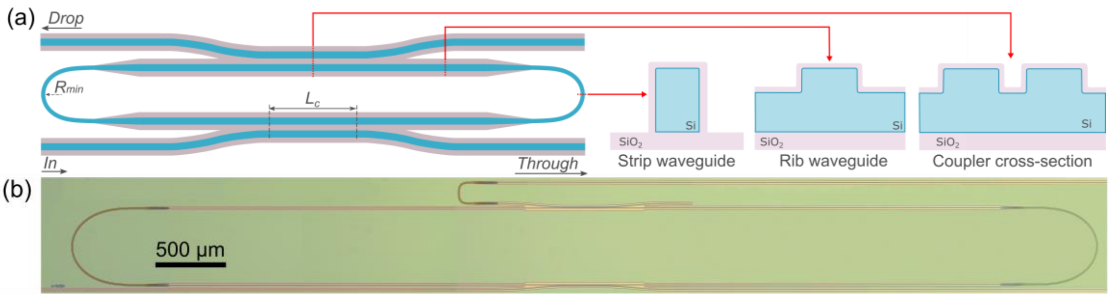

Fig. 1: (a) Schematic of the designed racetrack. Straight and coupling sections are based on single-mode rib waveguides, whereas the bends are based on multi-mode strip waveguides following an Euler curve. (b) Microscope image of the fabricated racetrack.

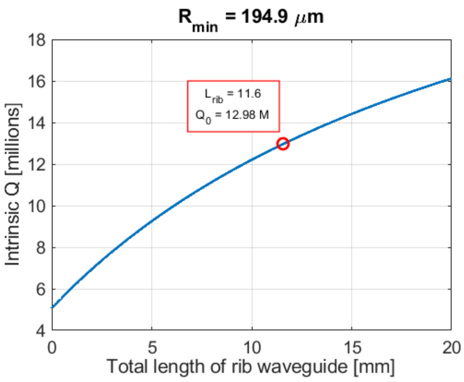

Fig. 2: Estimated intrinsic Q (Q_0) for the racetrack versus the total length of the straight rib waveguide section (L_{rib}).

achieve very tight bending radii with rib waveguides due to radiative coupling of higher order modes (HOMs) into the slab, we exploit Euler bends based on strip waveguides, which have a higher lateral confinement due to their higher index contrast, and therefore negligible coupling to HOMs, leading to lower bending losses [9]. To achieve single-mode operation with strip waveguides in VTT's thick SOI platform, sub-micron widths are needed, resulting in very high aspect ratio waveguides, which are prone to cracks due to stress, and also lead to higher propagation losses due to interaction of the optical field with the sidewall roughness. We have demonstrated bends using multi-mode waveguides with a 2 µm width and >99% transmission, supporting both TE and TM polarizations and with operation in a broad wavelength range using the so-called Euler bends [9]. For the transition between rib and strip waveguides we used efficient converters to allow coupling the single mode of the rib to the strip waveguide without HOMs excitation [9].

To determine the optimal matched bend radii for the U Euler bend, we simulated the transmission for different radii using FIMMPROP, and selected a minimum radius of 194.9 µm for a transmission of 99.98%. The length of the rib to strip converter was determined to be 200 µm to achieve an insertion loss of ~ 0.015 dB per converter. The racetrack was designed to be weakly coupled, meaning that the Q of the resonator is dominated by the propagation losses of the waveguide. Fig. 2 shows the estimation of the intrinsic Q versus the total length of straight rib waveguide sections of the racetrack, considering the previously mentioned bend radius and converter length. To estimate the intrinsic or loss Q, we need to know the propagation loss of the rib waveguides after hydrogen annealing smoothing. Before this process we measured a loss of 0.1 dB/cm [7], and we have also demonstrated a 3x reduction of the propagation loss in strip waveguides through hydrogen annealing, therefore we predicted a loss for the ribs of ~0.03 dB/cm after hydrogen annealing. From these estimations, we chose a total rib waveguide length of 11.6 mm to achieve a 12.98 million intrinsic Q.

Fabrication

The device was fabricated following a multi-project wafer run process at VTT. The waveguides were defined on 3 µm thick silicon wafers using stepper lithography (i-line), followed by dry etching with a Bosch process. This type of etching results in scallops on the sidewall that contribute to the sidewall roughness introduced during lithography (see Fig. 3). Previously at VTT, smoothing of the sidewall roughness was achieved through a thermal oxidation post-process, which considerably reduced the roughness. However, this process has some disadvantages such as the introduction of a linewidth reduction and rounding of the corners of the waveguides. These effects can be detrimental to the performance of some devices. Additionally, it is desirable to further reduce the scattering losses of silicon waveguides. We have already demonstrated a significant reduction of the propagation losses in strip waveguides on thick SOI through hydrogen annealing post-processing, showing preservation of the shape and dimensions of the waveguides [11]. Hydrogen annealing was originally proposed for sidewall smoothing in MEMS applications [12], and exploits the surface mobility of Si atoms at high temperatures, which results in smoothing of the sidewall. For the fabrication of the racetrack, the wafer was annealed in a 100 % pure hydrogen atmosphere, with a pressure of 70 Torr at 900 °C for 15 min. This process is completely MPW-compatible.

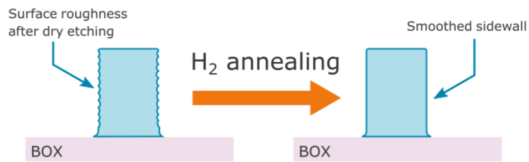

Fig. 3: Schematic illustrating sidewall smoothing by hydrogen annealing.

Experimental results

The measurement setup is shown in Fig. 4. The optical source was a tunable laser by Santec (TSL-550) with a 200 kHz linewidth, and for the detection we used a power meter module by Santec (MPM-211). Since we wanted to characterize the racetrack for both TE and TM polarizations, the setup includes a polarization control stage with a switch to select the proper input polarization, characterized by a polarization extinction ratio (PER) of ~20 dB. We coupled the light to the chip through edge coupling using tapered fibers to match the mode of the Si waveguides: a polarization maintaining fiber for the input and a standard single-mode fiber for the output.

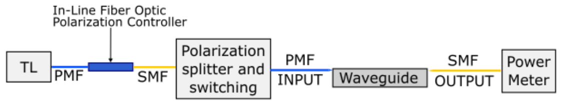

Fig. 4: Experimental setup schematic. TL: tunable laser, PMF: polarization maintaining fiber, SMF: single mode fiber.

The output spectrum for the through and drop port of the racetrack resonator between 1560.5 and 1561.5 nm is shown in Fig. 5(a) for TE and 5(b) for TM. Comparing the spectra for TE and TM, we can see that the coupling to the drop port for TE is higher than TM, this is due to the stronger confinement of the field for TM polarization, which translates into a weaker coupling coefficient between the input waveguide and the cavity. We can also observe in both spectra the presence of resonance notches in the through spectrum that are stronger than others and not aligned with the drop port resonance peaks. These correspond to the resonance of the opposite polarization since the setup has a finite PER and the waveguides have small polarization dependency, supporting both polarizations. This could be improved by increasing the PER of the setup or implementing a different approach to couple only one polarization into the cavity.

To determine the loaded Q of the racetrack we performed a Lorentzian fit of the resonance peaks of the drop port, and from these values we obtained the intrinsic Qs for each resonance. The calculated mean intrinsic Q for TE between 1560.5 and 1561.5 nm was 9.3 × 10^6, with a maximum value of 12.9 × 10^6 at 1561.13 nm, corresponding to a linewidth of 0.14 pm (17.69 MHz) and a propagation loss of ~2.8 dB/m (see Fig. 6(a)). For TM the mean intrinsic Q was 12.2 × 10^6, with a maximum value of 14.3 × 10^6 at 1560.61 nm, corresponding to a linewidth of 0.12 pm (14.84 MHz) and a propagation loss of ~2.7 dB/m (see Fig. 6(b)). These results are in good agreement with our estimation (see Fig. 2), particularly for TE polarization. The slightly higher Q for TM compared to TE is due to the stronger confinement of the optical field for TM, since this leads to less interaction with the sidewall roughness, and therefore, lower scattering losses.

Conclusions

We have experimentally demonstrated a racetrack with a maximum intrinsic Q of 13× 10^6 for TE and 14 × 10^6 for TM polarization, corresponding to a propagation loss for rib waveguides of ~2.8 dB/m and ~2.7 dB/m respectively, representing a significant reduction in the propagation losses, achieved thanks to sidewall roughness smoothing through an MPW-compatible hydrogen annealing post-etch process. These results will potentially enable development of emerging PIC applications.

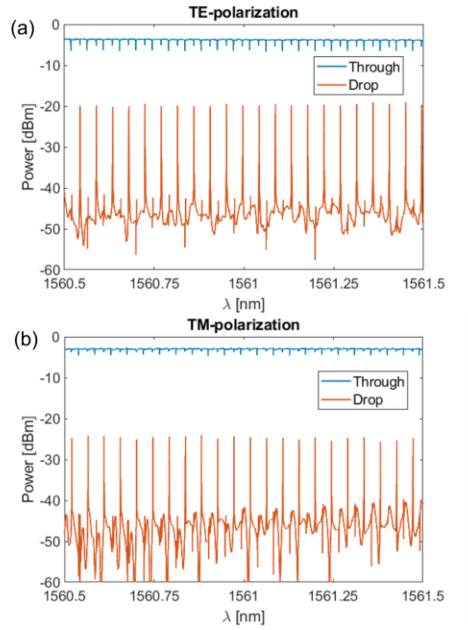

Fig. 5: Output spectrum of the drop and through ports of the racetrack for (a) TE polarization and (b) TM polarization.

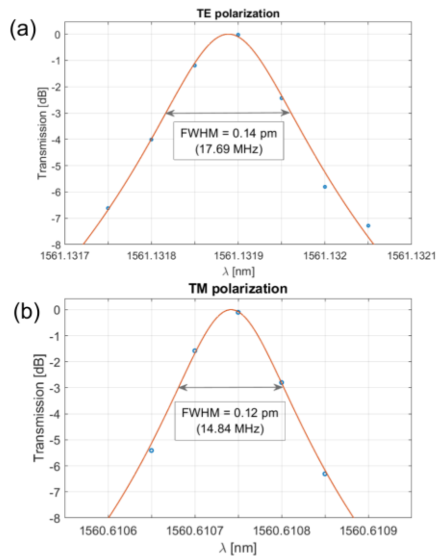

Fig. 6: Resonance peak with highest intrinsic Q (narrower linewidth) for (a) TE polarization and (b) TM polarization.

Acknowledgements

The work is part of the Academy of Finland Flagship Programme, Photonics Research and Innovation (PREIN), decision number 320168.

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