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Compact silicon microring resonators with ultra-low propagation loss in the C band

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Abstract – The propagation loss in compact silicon microring resonators is optimized with varied ring widths as well as bending radii. At the telecom band of 1.53-1.57 μm, we demonstrate as low as 3-4 dB/cm propagation losses in compact silicon microring resonators with a small bending radius of 5 μm, corresponding to a high intrinsic quality factor of 200,000-300,000. The loss is reduced to 2-3 dB/cm for a larger bending radius of 10 μm, and the intrinsic quality factor increases up to an ultrahigh value of 420,000. Slot-waveguide microring resonators with around 80% optical power confinement in the slot are also demonstrated with propagation losses as low as 1.3±0.2 dB/mm at 1.55 μm band. These loss numbers are believed to be among the lowest ones ever achieved in silicon microring resonators with similar sizes.

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1. Introduction

The high-index-contrast in silicon-on-insulator (SOI) waveguides allows small bending radii with low propagation losses, leading to compact resonators and high-density integration of micro-photonic devices. However, propagation losses due to waveguide sidewall roughness and small bending radii may be prohibitively large for highly integrated SOI photonic devices. Extremely low-loss SOI strips were reported by reducing waveguide roughness with post-fabrication trimming techniques [1]. In this paper, without post-fabrication trimming, we demonstrate ultra-low propagation losses of 3-4 dB/cm and 2-3 dB/cm in the entire C band in compact silicon microring resonators with bending radii of 5 μm and 10 μm, respectively. The corresponding round-trip losses are around 0.01-0.02 dB. Our reported losses in microring bends are comparable to the latest reports on propagation losses in silicon strips, e.g., 1.7±0.1 dB/cm (with post-fabrication trimming) [2], 3.6±0.1 dB/cm [3], 2.4±1.6 dB/cm [4] and 2.8 dB/cm [5]. This indicates that the bending loss is negligible compared to the linear propagation loss due to sidewall roughness. As a result, such low-loss microring bends may be treated as strips. Our reported lowest loss numbers in microrings are slightly lower than other ones for similar bending radii, *e.g.*, 0.02-0.03 dB/round-trip for a bending radius of 6.5 μm [2] and 0.004 dB per 90° bend for a bending radius of 5 μm [6]. Compared to the work on low-loss silicon microring resonators with a large bending radius of 20 μm in [7], we show comparable ultrahigh intrinsic quality factors of 200,000-300,000 in microring resonators with a four times smaller radius, and a higher intrinsic quality factor of 300,000-400,000 for a two times smaller bending radius. Thus our result enables more compact footprint of devices based on high-Q silicon microring resonators. Comparable results were briefly reported in [8] but without experimental details. There have been great interests in exploring the light confinement in slot-waveguides [9-10], which have also been used for active silicon photonic devices [11-12]. The void structure provides many opportunities for novel photonic applications. Here, we report 1.3±0.2 dB/mm propagation loss in the microring resonator based on slot-waveguides with around 80% optical power confined in the slot. This loss number is comparable to previous best-reported values in [9] but in a five times smaller ring resonator, and we also demonstrate slot-waveguide silicon microring add-drop filter for the first time as previous slot-waveguide resonators were coupled to only a single waveguide.

Recently, we reported a new method to analyze the propagation loss in microring resonators [13]. Figure 1 shows the schematic of a symmetrically coupled microring resonator. κ^2 is defined as the fraction of power coupling between the bus waveguide and the microring resonator. All losses other than the bus-ring coupling, including the bending loss and radiation loss due to sidewall roughness, is lumped into a parameter κ_p^2, which is the fraction of propagation power loss per round-trip in the microring resonator. We define the minimum power transmission in the through-port as γ, the drop -3dB bandwidth as $\delta\lambda_d$, and the response period of the resonator as *FSR* (free spectral range). The waveguide power coupling coefficient is calculated to be $\kappa^2= \pi\times(\delta\lambda_d)\times[1-(\gamma)^{1/2}]/FSR$, and the propagation power loss coefficient is determined to be $\kappa_p^2= 2\pi\times(\delta\lambda_d)\times(\gamma)^{1/2}/FSR$ [13]. To be compared with the losses in straight waveguides, which is often quoted in dB/cm, the propagation loss in a microring resonator can be expressed as $-10\times log_{10}(1-\kappa_p^2)/(2\pi R)$ (dB/cm), where 2πR is the perimeter of the microring resonator. The total quality factor is defined as $Q_t = \lambda_o/\delta\lambda_d$

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$=(2\pi\lambda_o)/[FSR\times(2\kappa^2+\kappa_p^2)]$, and the intrinsic quality factor is $Q_i=(2\pi\lambda_o)/(FSR\times\kappa_p^2)=Q_t/(\gamma)^{1/2}$. We would like to comment briefly here on advantages of our method. For details, please refer to reference [13]. Compared to the well-known cut-back or Fabry-Pérot methods, our method in principle is independent of fiber-to-waveguide coupling or cleaved waveguide facets. In particular, our method is very useful in determining the very low propagation losses in waveguides and/or bends from the response of a single resonator in add-drop configuration. It does not require the fabrication of many waveguides of various lengths and/or bends for accurate measurement. Compared to the well-known critical coupling method, ours does not require the tedious fabrication of many devices in order to obtain critically coupled resonators in all-pass configuration, which demands well matched waveguide coupling and resonator's loss, *i.e.*, $\kappa^2=\kappa_p^2$. Furthermore, for symmetrically coupled add-drop filters based on microring resonators, our method gives an *in-situ* loss analysis, avoiding the device non-uniformities that result from fabrication.

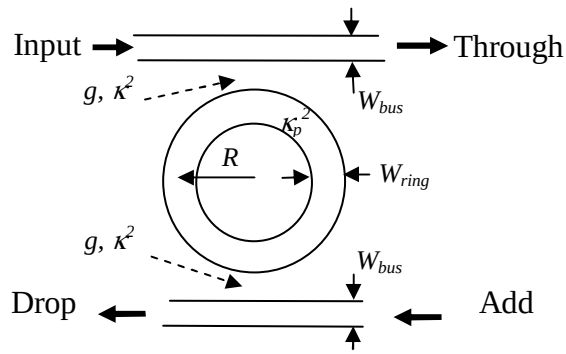

Fig.1. Schematic of a symmetrically coupled microring resonator.

2. Device fabrication

Our devices were fabricated on a silicon-on-insulator (SOI) wafer with a top silicon layer thickness of 250 nm and a buried oxide thickness of 3 μm. The device patterns were exposed in a 150 nm-thick negative resist (hydrogen silsesquioxane, or HSQ) with a Vistec VB6 UHR-EWF electron-beam lithography (EBL) system at 100kV. The main beam deflection field size was 0.5mm×0.5mm, and the beam deflection step was 2 nm. For as smooth as possible waveguide line edges, we put large number (~ 2,800) of vertices in a polygon to approximate the rings in the layout. This minimizes pattern digitization error and reduces waveguide line-edge roughness. The electron beam has a spot diameter of around 5 nm, and this helps to round out pattern digitization error due to the discrete beam deflection step (2 nm) in exposures. The development of HSQ was done in 25% TMAH for 1 minute to improve the contrast. Inductively-coupled-plasma (ICP) reactive-ion-etch (RIE) was then applied to etch through the 250 nm silicon layer. The chamber pressure was 2 mTorr and the gases were Cl_2 and Ar with flow rates of 15 sccm and 5 sccm respectively. The HSQ mask was kept intact as a top cladding layer during device characterization as the HSQ has a refractive index ~ 1.4 and a very low absorption loss at 1.55 μm bands [14]. According to our measurements in this paper, the HSQ does not appear to affect the optical performance in high-index-contrast silicon waveguides.

It is known that the propagation loss is sensitive to the width of silicon waveguides, so we fabricated five sets of microring resonator with the same radius of 5 μm but different ring waveguide widths of 400, 450, 500, 550 and 600 nm. The microring waveguides are approximately of single mode (TE) at ~ 1.55 μm telecom band for widths up to 600 nm, and other modes have much higher propagation loss in the strongly bended microring waveguides. Figure 2 shows scanning-electron micrographs of one fabricated microring resonator with

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waveguide width W_{ring} ~ 500 nm and waveguide cross-sections at two cleaved facets. W_{bus} is fixed at 500 nm for all fabricated devices in this paper. The gap (g) between the bus waveguide and the ring is ~ 300 nm. The highly magnified (×100K) image of the ring waveguide shows a very smooth line edge. The line edge roughness is estimated to be ≤ 5 nm, which is mainly limited by the mixed effect of the digitization error and the finite beam spot size in EBL. Additionally, the waveguide width may have very slight variations due to the beam deflection errors, which are up to 10 nm over the entire field of 0.5 mm×0.5 mm according to machine calibrations. As the microring's footprint (e.g., 10 μm×10 μm) is very small compared to the whole writing main field, the effect of beam deflection errors is expected to be small. The sidewall smoothness and the line-edge smoothness are confirmed with waveguide cross-section images in Fig. 2. Slight over-etch into the buried oxide can be observed.

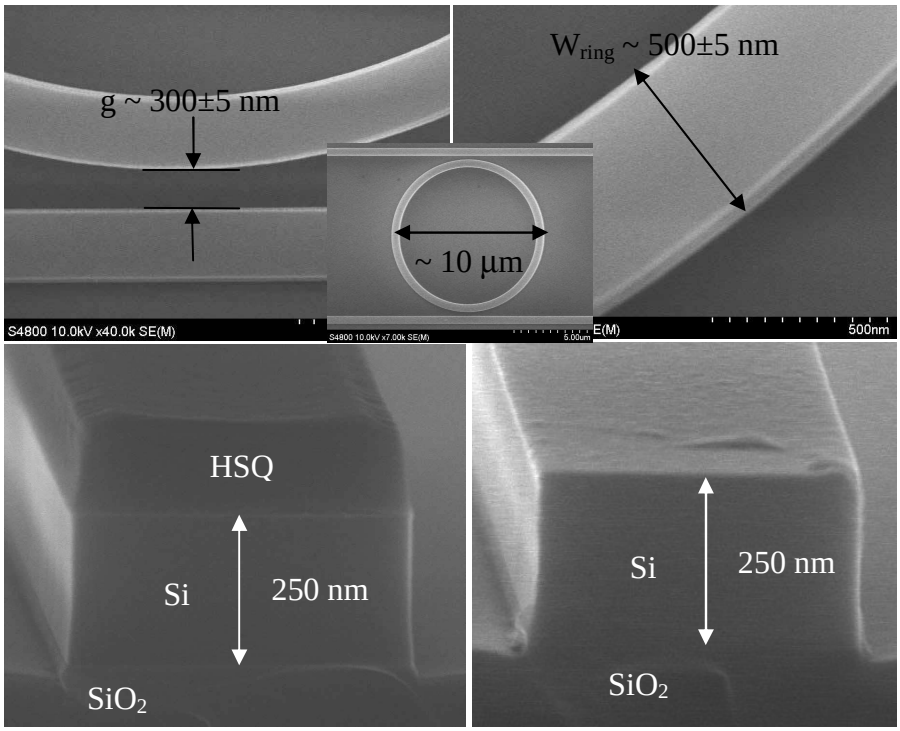

Fig. 2. Scanning electron micrographs of a fabricated microring resonator and waveguide cross-section at two cleaved facets.

3. Analysis of propagation loss

Figure 3 shows the measured responses (power transmission spectrum) of a representative microring resonator as illustrated in Fig. 2. In Fig. 3(a), we show the drop-port response over the C band, and a very high filtering contrast ≥ 30 dB is demonstrated. The average FSR is 16.0±0.1 nm. In Fig. 3(b) we use much finer wavelength steps to scan a particular resonance in order to accurately measure the through-port extinction and the drop bandwidth. The red line in Fig. 3(b) is the measured through-port response, showing a high extinction of 24±0.5 dB (γ = 0.004 ± 0.0005). The blue line represents the measured drop-port response, with a -3dB bandwidth of $\delta\lambda_d$ = 0.11±0.01 nm and an ultra-low drop-loss (≤ 1dB). These lead to a total quality factor Q_t of 14,000±1100 at ~ 1524.6 nm. The extracted power loss coefficient κ_p^2 is 0.0027±0.0004 (Q_i = 220,000±30,000), and the corresponding propagation loss is

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3.7±0.5 dB/cm. The coupling coefficient κ^2 is determined to be 0.02±0.002. Following the same procedure, we extracted all propagation losses and intrinsic quality factors for the other two resonance wavelengths in C band as well as for other resonators with different W_{ring} of 400, 450, 550 and 600 nm. In all resonators, the coupling gap between the bus waveguide and the ring was fixed at 300 nm in design.

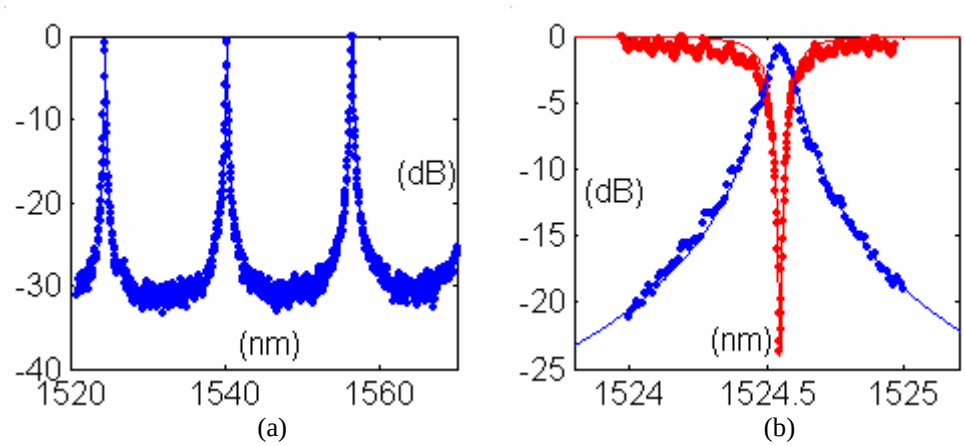

Fig. 3. Measured responses of a microring resonator similar to the one shown in Fig. 2. (a) is a general view of the drop-port response, (b) is a zoom-in view of through-port and drop-port responses scanned with much finer wavelength steps than that in (a).

Figures 4(a) and 4(b) illustrate the extracted propagation losses and intrinsic quality-factors, respectively, as functions of the ring width and the wavelength over C band. For rings width $W_{ring} \leq$ ~ 500 nm, the propagation loss increases significantly as wavelengths increase across the entire C band. This is likely due to the fact that the bending dominates the loss and the bending loss increases significantly in bends with smaller waveguide width ($W_{ring} \leq$ ~ 500 nm) due to lower optical confinement at larger wavelengths. For rings width $W_{ring} \geq$ ~ 550 nm, the propagation losses are very low < ~5 dB/cm and do not change significantly over the C band. The lowest extracted propagation loss we observed is 3.5±0.3 dB/cm (intrinsic quality factor Q_i = 240,000±24,000) for W_{ring}=600 nm at the wavelength ~ 1.55 μm.

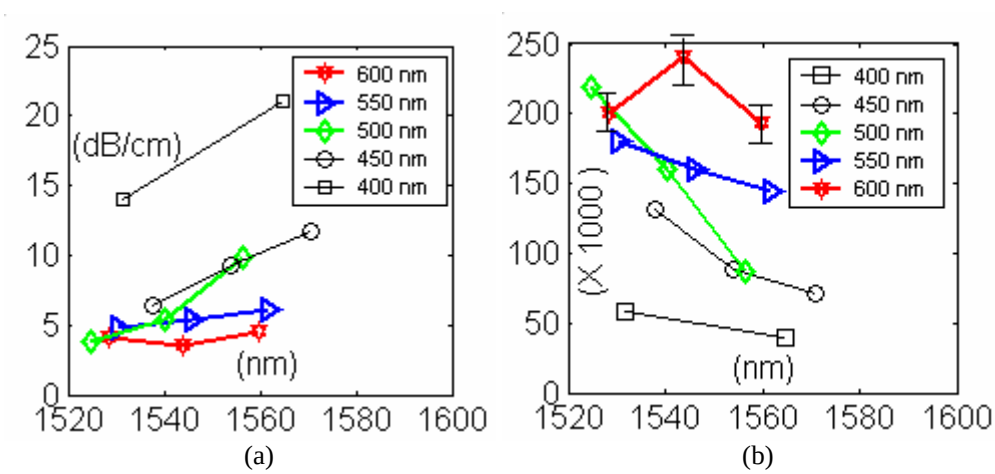

Fig. 4. Extracted propagation losses (a) and extracted intrinsic quality factors (b) in microring resonators with different ring widths (W_{ring} = 400, 450, 500, 550, and 600 nm) but the same core height of 250 nm. The bending radius is 5 μm.

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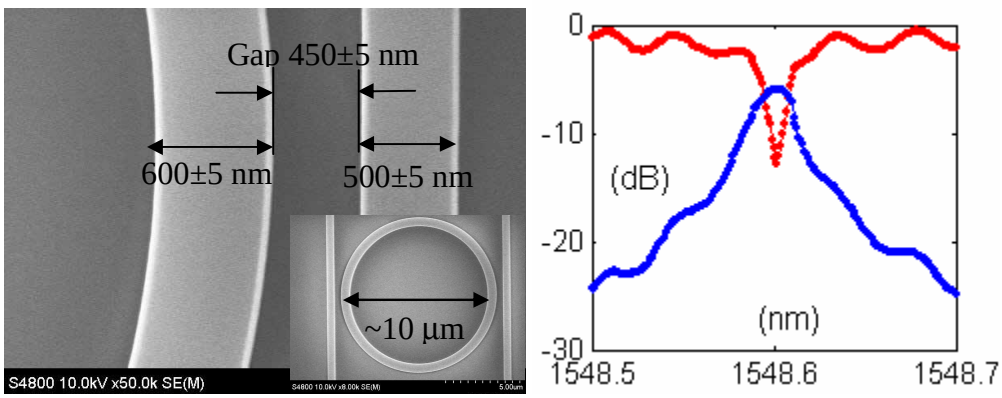
One very important issue is the accuracy of the extracted such high intrinsic quality factors (> 200,000) and such low propagation losses (< 4 dB/cm). The accuracy of κ_p^2 is very sensitive to small errors in measuring high through-port extinctions of 20 dB or more. In Fig. 3(b), the sharp resonance notch in the through-port only has a 3dB bandwidth of several picometers, which is close to our tunable laser wavelength resolution (1 pm). For a strip waveguide with cross-section of 500 nm × 250 nm, instead of the lowest TE mode, we also observed the lowest TM mode. This TM mode has higher propagation loss, but will not resonate at the wavelength of TE mode resonance, thus remaining in the waveguide. Therefore it may reduce the through-port extinction of the lowest TE mode, leading to a larger measured γ. According to $Q_t = \lambda_o/\delta\lambda_d/(\gamma)^{1/2}$, the actual intrinsic quality factor could be larger.



(a) (b)

Fig. 5. (a) Scanning-electron micrographs of one fabricated weakly coupled microring resonator. (b) zoom-in view of through-port and drop-port responses scanned with 1 pm wavelength step.

In order to verify the achieved low propagation losses and high intrinsic quality-factors, weakly coupled microring resonators were also fabricated and tested. Figure 5(a) shows scanning electron micrographs of one fabricated microring resonators with weak waveguide coupling. The ring width W_{ring} is ~ 600 nm, and the bus waveguide width W_{bus} is ~ 500 nm. The coupling gap is increased to ~ 450 nm. Figure 5(b) is a zoom-in view for the responses at wavelengths ~1.55 μm. For the resonance at 1548.6 nm, we have γ= 0.053 ± 0.005 (~ 13 dB extinction) and $\delta\lambda_d$ = 0.025±0.001 nm, corresponding to a total quality-factor Q_t ~ 62,000. The extracted waveguide coupling coefficient k^2 is 0.0038±0.0004, and the extracted power loss coefficient k_p^2 is 0.0022±0.0002. The propagation loss is 3.0±0.3 dB/cm, and the corresponding intrinsic quality factor Q_i is 270,000±27,000. The loss number verifies that we have indeed achieved low propagation loss of 3-4 dB/cm and high intrinsic quality-factors of 200,000-300,000 at telecom wavelengths in compact microring resonators with a radius of 5 μm. We believe these loss numbers are among the lowest ones without any post-fabrication trimming in silicon microring resonators or waveguides.

To understand the bending effect on the propagation loss, we also fabricated and tested microring resonators with two other radii of 10 μm and 2.5 μm. Figures 6(a) and 6(b) show measured responses of through-port and drop-port in one fabricated resonator with 10 μm bend radius (W_{ring} = 600 nm). For the resonance at ~ 1.53 μm, FSR = 7.7±0.05nm, γ= 0.021 ± 0.002 (~ 17 dB extinction) and $\delta\lambda_d$ = 0.022±0.001 nm (Q_t ~ 70,000). Consequently, κ_p^2=0.0022±0.0002, and the propagation loss is 1.8±0.2 dB/cm or 0.011±0.001 dB/round-trip (Q_i=422,000±40,000). For the resonance at ~ 1.56 μm, the propagation loss is 2.8±0.3 dB/cm or 0.017±0.002 dB/round-trip (Q_i=320,000±30,000). Compared to the microring resonator with R=5 μm, the resonator with R=10 μm shows obviously lower propagation losses across

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the C band due to the smaller bending curvature. Figures 7(a) and 7(b) show extracted propagation losses and intrinsic quality-factors, respectively, as functions of the ring width (400, 500 and 600 nm) and the wavelength over C band. Compared to the microring with 5 μm bending radius, for 10 μm bending radius, the propagation loss shows a significant lower number for W_{ring} = 400 nm, and it is also less wavelength dependent. In Fig. 7, for W_{ring} = 400 nm, we plotted propagation loss and intrinsic quality-factor for two microrings fabricated on the same chip but at different locations, and there were some variations attributed to fabrication-induced variations. For rings widths of W_{ring} = 500 or 600 nm, the propagation loss is very low (~ 2-4 dB/cm) over the C band. These observations indicate that the bending loss is obviously smaller for 10 μm bending radius than that for 5 μm bending radius.

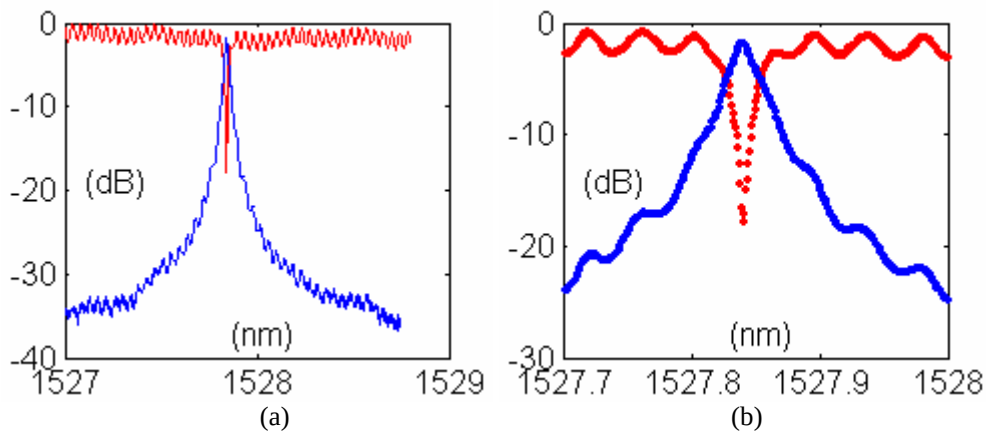

Fig. 6. Measured responses of the through-port and drop-port of a microring resonator with R=10 μm. (b) is a zoom-in view of (a).

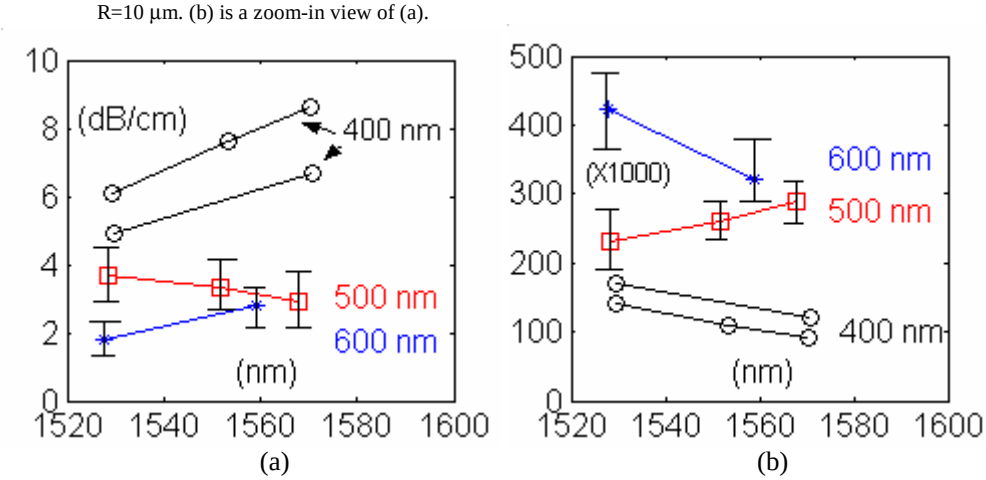

Fig. 7. Extracted propagation losses (a) and extracted intrinsic quality factors (b) in microring resonators with different ring widths (W_{ring} = 400, 500, and 600 nm) but the same core height of 250 nm. The bending radius is 10 μm.

On the other hand, for a 2.5 μm bend radius, the propagation loss increases dramatically by an order of magnitude or more for small ring width, and this high loss is mainly attributed to the bending loss in small microrings with R = 2.5 μm (only around four times of the guided wavelength in silicon). The lower bound for the propagation loss and the upper bound for intrinsic quality factor can be understood mathematically here. For a very small κ_p^2 in low-loss microring resonators, the propagation loss can be approximated by $-10\times log_{10}(1-$

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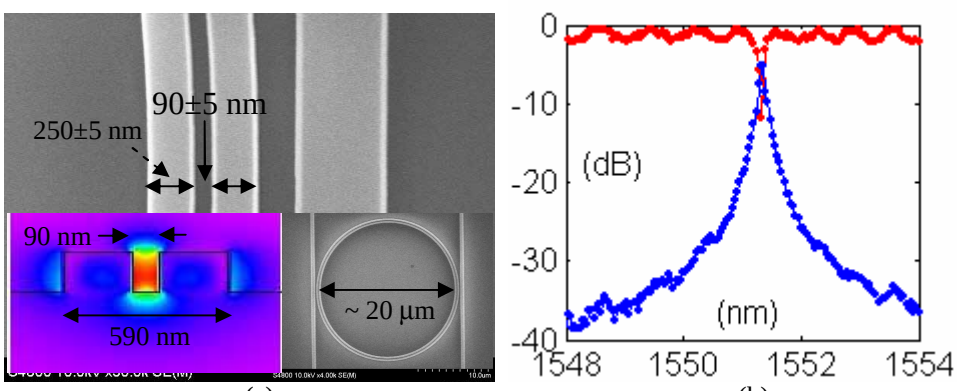
$k_p^2)/(2\pi R) \approx 4.34 \times \kappa_p^2/(2\pi R)$, which is roughly constant if the propagation loss is dominated by the linear propagation loss, and the intrinsic quality-factor also stays approximately the same according to $Q_i = (2\pi\lambda_o)/(FSR \times \kappa_p^2) = (4\pi^2 n_g/\lambda_o) \times (R/\kappa_p^2)$.

4. Slot-waveguide microring resonator

Figure 8(a) shows scanning-electron micrographs of one fabricated slot-waveguide microring resonator and the simulated slot-mode (major e-field) amplitude profile. The radius of the microring is 10 μm. The light is coupled into the slot-waveguide microring resonator with a regular silicon waveguide. The slot has a width ~ 90 nm, and the width is ~ 250 nm for each slot arm. The mode is simulated with Rsoft BPM, and the power confinement factor in the slot area is around 80±10%. Figure 8(b) shows experimental add-drop response. The *FSR* is 10.1±0.1 nm at ~ 1.55 μm, and a total quality-factor Q_t is ~ 14,100. The extracted propagation loss is 1.3±0.2 dB/mm (Q_i=52,000±3,000). In addition, we also fabricated and tested another slot-waveguide microring resonator with a radius of 5 μm, and the extracted propagation loss (12±1 dB/mm at 1.55 μm) is an order of magnitude higher than that in the slot-waveguide microring with a radius of 10 μm and nearly two orders of magnitude higher than that in the regular waveguide microring with the same radius of 5 μm. This large propagation loss indicates that sidewall roughness scattering loss is very large in slot-waveguide with small bending radius like 5 μm, since a major portion (around 80%) of the optical power is inside the slot of only ~ 90 nm wide.



(a) (b)

Fig. 8. (a) Scanning-electron micrographs of one fabricated slot-waveguide microring resonator and the simulated slot-mode (amplitude) picture. (b) One measured add-drop response.

5. Conclusion

In summary, without post-fabrication smoothing, we have demonstrated ultra-low propagation losses in compact silicon-on-insulator microring resonators, using optimized lithography and etch processes. The propagation loss was optimized by a by varying both the ring width and the bending radius. For a waveguide core cross-section of ~ 600 nm × 250 nm, the loss was found to be consistently 3-4 dB/cm and 2-3 dB/cm over the entire C band for bending radii of 5 μm and 10 μm, respectively. For waveguide core cross-sections below ~ 500×250 nm, the propagation losses in 5 μm-radius rings increase appreciably at larger wavelengths. The lowest propagation loss number we achieved was 1.8±0.2 dB/cm at 1.53 μm for a 10 μm bending radius, corresponding to an intrinsic quality-factor of 422,000±40,000. To our best knowledge, the loss of 1.8±0.2 dB/cm is the lowest one ever published for a rectangular submicron silicon

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waveguide without post-fabrication trimming, and the corresponding intrinsic quality factor of 422,000±40,000 is the highest one reported for any silicon microrings of similar bending radii. Slot-waveguide microring resonators were also fabricated, and a relatively low propagation loss of 1.3±0.2 dB/mm (an intrinsic quality-factor of 52,000±3,000) was achieved at 1.55 μm in a slot-waveguide with a bending radius of 10 μm and around 80% optical power confined in the slot.

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