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A Taper to Reduce the Straight-to-Bend Transition Loss in Compact Silicon Waveguides

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A Taper to Reduce the Straight-to-Bend Transition Loss in Compact Silicon Waveguides

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***Abstract*—Strong confinement of light in silicon waveguides allows for sharp bends and, as a result, high-density integration. However, the mode transition loss between the straight and bent portions of a silicon waveguide begins to affect the device performance when the bending radius becomes small. In this letter, we show that a transition region with a step taper between the straight and bent portions of the waveguide can effectively reduce this transition loss. This is demonstrated by measuring the intrinsic round-trip losses of micro-racetrack resonators, where ultralow loss can be precisely characterized according to the quality (Q)-factor change. The results show that the taper can suppress the transition loss from 0.016 to 0.0022 dB for a 4.5-μm bend radius. Consequently, we improve the Q-factor of such a racetrack resonator from 31 000 to 87 000.**

***Index Terms*—Micro-resonator, Si waveguide, transition loss.**

I. Introduction

SILICON photonics has drawn significant interest since it provides complementary metal–oxide–semiconductor (CMOS) compatibility for integrated optical systems. Silicon photonic microstructures have achieved functionalities such as delay lines [1], filters [2], and modulators [3]. As one of the basic elements of silicon photonic devices, silicon waveguides, including straight sections and bends, need to have extremely low propagation loss [4]–[6], for large-scale integration and low power consumption. The loss in a straight silicon waveguide is mainly from scattering due to side-wall roughness, leakage to the substrate, and material absorption [4], [6]. Such losses come from fabrication processes and wafer structure, and cannot be mitigated with geometric design of the devices. Other types of losses come from certain waveguide geometries, such as bending loss and straight-to-bend transition loss [7]. They are usually negligible compared to the propagation loss when the bending radius is large, e.g., hundreds of micrometers. However, for ultracompact silicon photonics devices, such as microring resonators, which typically have bending radii at 10 μm or below, these losses may be nontrivial and need to be characterized and mitigated. In this letter, we propose and demonstrate a simple, easy-to-generate taper design to reduce the transition loss between straight and bent waveguide sections, and use it to realize a racetrack micro-resonator with a high quality (Q)-factor. This will help, for example, to pack long silicon waveguides with a small footprint, where many 90° and 180° turns exist.

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II. Theory

In a waveguide bend, the mode profile tends to shift toward the outer edge of the waveguide, making it intrinsically lossy. Fortunately, silicon has a high refractive index so that the optical power is still tightly confined within the waveguide area. As a result, the waveguide bending loss can be neglected even at relatively small bending radii (e.g., 5 μm). The high Q-factor of microring resonators at around 300 000 [8], [9] is proof of the low loss in waveguide bends. However, for another popular type of resonator, micro-racetrack, the Q-factor has not reached such a high value [10]. One of the main reasons is the mode-mismatch loss between the straight and bent portions of the waveguide in the racetrack geometry, which does not exist in ring resonators. This type of loss has been previously investigated by numerical methods [7], [11]. The loss is quite small when the bending radius is larger than 5 μm for a strip silicon waveguide. However, in a resonator cavity, such a small loss will degrade the Q-factor by a large amount.

There are several ways to measure the waveguide loss, such as the cut-back and the Fabry–Pérot method [12]. Unfortunately, these methods are susceptible to the nonuniform waveguide facets and are not well-suited to measure very low losses precisely. In this letter, we analyze the intrinsic round-trip loss of a micro-racetrack to obtain the transition loss. Since these resonators have high Q-factors, our method is very sensitive to the small additional losses in transition regions.

A general travelling wave resonator can be modeled with a waveguide cavity coupled to two waveguides, the through port and the drop port [Fig. 1(a)]. κ_e^2 and κ_d^2 indicate the fraction of power coupled from the through and drop port to the cavity. κ_l^2 is the intrinsic loss (including scattering, bending, and mode mismatch, etc.) per round-trip within the micro-resonator. Based on coupling mode theory in the time domain, we have developed a method [13] to calculate the intrinsic loss by measuring the through port and drop port power spectra

$$\kappa_l^2 = 2\pi \times (\delta\lambda_d) \times (\gamma_t)^{1/2}/\mathrm{FSR}. \quad (1)$$

Here $\delta\lambda_d$ is the 3-dB bandwidth of the drop port spectrum. γ_t is the minimum power of the through port spectrum at resonance, and FSR is the free spectral range of the cavity. This function is valid on the condition that $\kappa_e^2 = \kappa_d^2$. The intrinsic Q-factor ($Q_{\mathrm{intrinsic}}$) is then calculated as

$$Q_{\mathrm{intrinsic}} = (2\pi\lambda_o)/(\mathrm{FSR} \times \kappa_l^2). \quad (2)$$

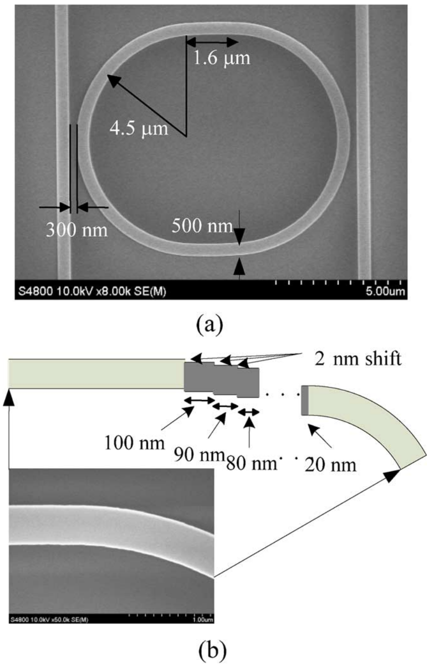

Fig. 1. Scanning electron microscope (SEM) picture of the fabricated racetrack resonator with transition taper between the straight and bent sections. (a) shows the resonator and (b) illustrates the transition taper structure.

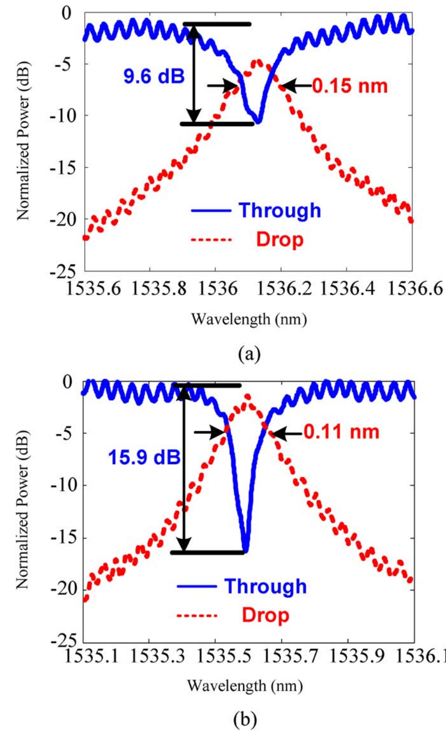

Fig. 2. Through and drop port power spectrum of micro-racetrack resonator (a) without and (b) with transition taper.

III. Experiment and Results

We fabricated micro-racetrack resonators to quantitatively investigate the mode transition losses. The taper was designed as a stair-case with decreasing stair width. This provides a gradual shift in the radius of curvature, in contrast to the direct connection from a straight line to a semicircle in a traditional racetrack design [Fig. 1(b)]. Each stair step has decreasing length with extremely small (2 nm) lateral shift to minimize the mode mismatch from straight to bent portions of the waveguide. The taper part is reasonably short (0.54 μm) so that it can be applied in very compact resonators. In Fig. 1(a), the taper together with the straight waveguide section is 1.6 μm long.

The silicon waveguide has a cross-section of $500\ \text{nm} \times 250\ \text{nm}$. The gaps between the racetrack's bends and coupling waveguides are fixed at 300 nm. Our devices were fabricated on a silicon-on-insulator (SOI) wafer. The top silicon layer thickness is 250 nm and the buried oxide is 3 μm thick. The device patterns were exposed in 200-nm-thick hydrogen silsesquioxane (HSQ) with a Vistec 100-kV electron-beam lithography (EBL) system with a 2-nm beam step. Etching of silicon was done with a Panasonic E620 tool with Chlorine plasma. Infrared light was guided into and out of the waveguide using lensed fiber tips. Polarization was adjusted with a fiber-based polarization controller. The fiber-to-fiber loss is 25 dB without employing any fiber-to-waveguide taper.

On the same chip as the micro-racetrack resonator, we fabricated a microring resonator with a 5-μm radius as reference. The perimeter of the microring resonator (10π μm) is identical to the racetrack showed in Fig. 1 so that they resonate at roughly the same wavelength. The measurement result gave us a 20.6-dB through port extinction ratio and 0.07-nm drop port 3-dB bandwidth. According to (1), the round-trip loss is 0.5%, which corresponds to an intrinsic Q-factor of 240 000. The number can be translated into a waveguide propagation loss of 3.5 ± 0.5 dB/cm. As the bending loss can be neglected at a 5-μm radius [4], we can treat 3.5 ± 0.5 dB/cm as the propagation loss in silicon waveguides, whether straight or bent at a 5-μm radius.

We then measured a micro-racetrack resonator with the same perimeter as the one shown in Fig. 1(a), but without transition tapers. The power spectrum is shown in Fig. 2(a). The round-trip loss is calculated to be 1.95% with an intrinsic Q-factor around 31 000 at 1536.1 nm. Compared to the reference microring resonator, the additional loss in the micro-racetrack is attributed to the mode transition loss at the straight-to-bend regions. Each transition region contributes to the loss by $0.36\% \pm 0.05\%$, which equals 0.016 ± 0.002 dB per transition. The uncertainty exists here mainly because the extinction ratio reading is influenced by Fabry–Pérot fringes in the power spectrum. Still, we clearly see the loss introduced by each transition is at a level similar to the total loss in a microring resonator. It greatly degrades the Q-factor of the micro-racetrack resonator and will easily accumulate to a significant level in complicated systems where hundreds or more transitions will be included. Fortunately, Fig. 2(b) shows highly effective improvement with our transition connector design. The intrinsic Q-factor is increased to 87 000 at 1535.6 nm. Thus the loss is now $0.05\% \pm 0.01\%$, or 0.0022 ± 0.001 dB per transition. The transition loss has been successfully reduced to 14% of the previous value and the Q-factor is tripled. The slight difference in resonance wavelength is due to the perimeter variation from the design and fabrication imperfection.

Table I shows the measurement results at two successive resonance wavelengths of the resonator. Slight increase in transition loss is expected as the confinement is weaker for larger wavelengths. With this demonstration, the high Q-factor micro-racetrack resonator becomes increasingly beneficial for various ap-

TABLE I
CHARACTERIZATION OF RACETRACK RESONATORS

Wavelength (nm)	Extinction Ratio (dB)	Drop Port 3-dB Bandwidth (nm)	Loss per Transition (dB)
Racetrack Resonator without transition taper			
1551.8	10.3	0.24	0.026
1568.1	10.9	0.22	0.021
Racetrack Resonator with transition taper			
1551.4	15.5	0.15	0.0054
1567.5	16.1	0.20	0.0079

plications. For example, the optical delay line [1] generally contains tens to hundreds of micro-racetrack resonators. In such an application, racetracks can provide strong and controllable coupling strength. The insertion loss in this device is generally high and could be reduced significantly with our transition taper idea. Recently, high Q-factor micro-racetrack cavities were also reported [6] using deep ultraviolet lithography, but without applying transition tapers. Thus our method may apply another route to increase the Q-factor of micro-racetrack cavities.

IV. Discussion

It is desirable to reduce the transition loss for even smaller bending radii. We applied the same taper mentioned above for a bending radius of 2.5 μm, and preliminary results showed that the transition loss decreased from 0.076 to 0.03 dB. A modified taper design, which increases the stair step from 2 to 4 nm, gave 0.019-dB loss per transition since a steeper stair step matches the decreased bending radius better.

These results show that the optimum taper design is dependent on the bending radius of the racetrack. We applied the modal overlap method to estimate the transition loss between straight and bent waveguides and the results were of the same order-of-magnitude as our measurement. To further optimize the taper design, more precise three-dimensional finite-difference time-domain (3-D FDTD) simulations are required to estimate losses as small as 10^{-3} dB. However, to reach this accuracy, a very small grid size (2 nm) is needed. Simulation at this resolution will require a large amount of memory and computer time. Additionally, in fabrication, the EBL system has a larger beam spot size ($\sim$5 nm) than the beam step size (2 nm), which helps to smooth out the 2-nm shift between the steps and create a smooth curve. The simulation tool currently cannot take into account this effect, and numerical results may not be accurate. With the experimental results in this letter, we plan to develop numerical methods to estimate such losses in a faster way and use it to optimize tapers for even smaller bending radii.

V. Conclusion

We proposed and demonstrated a novel transition taper to reduce the transition loss between straight and bent portions of a compact silicon waveguide and achieved high Q-factors in micro-racetrack resonators with a bending radius at 4.5 μm. At 1536 nm, the transition loss was suppressed from 0.016 ± 0.002 dB to 0.0022 ± 0.001 dB per transition. The intrinsic Q-factor of the micro-racetrack resonator was improved from 31 000 to 87 000. Our method will help reduce the insertion loss of silicon photonics devices such as long silicon wires and micro-resonator-based delay lines.

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