High quality factor trapezoidal subwavelength grating waveguide micro-ring resonator
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ABSTRACT
In recent decades, silicon photonics has attracted intensive research interest in optical communications due to its advantageous compact dimensions and high-volume manufacturability. Particularly, micro-ring resonators on silicon-on-insulator (SOI) platform have been widely exploited as a basic building block for a vast range of applications such as switches, modulators, and sensors. A majority of these applications involve light-matter interaction, which can be substantially enhanced by the high quality factor micro-ring resonators. However, conventional strip waveguide based micro-ring resonators suffer from the intrinsic dilemma in achieving high light confinement and strong light-matter interaction simultaneously. Subwavelength grating (SWG) waveguides, comprised of periodically interleaved high and low refractive index materials with a pitch less than one wavelength, have been demonstrated as a promising alternative. For SWG waveguides built on SOI wafers, the ratio of silicon and cladding materials can be engineered microscopically to achieve desired macroscopic properties. The control of these properties could potentially lead to significant performance improvements compared with conventional micro-ring resonators based photonic devices, such as filters and sensors. However, SWG waveguide based micro-ring resonators (SWGMRs) that have been demonstrated so far can only provide a moderate quality factor (~5600) with a large radius (e.g. 15 μm), which greatly jeopardize the wide spread research efforts in this area. In this paper, we propose to use trapezoidal silicon pillars to reduce the bend loss of SWGMRs to improve the quality factor. For the first time, we experimentally demonstrate the smallest SWGMR (the micro-ring radius equals to 5 μm) with an applicable quality factor as high as 11,500. This approach also can be applied to SWGMRs with larger radii for higher quality factors. We also experimentally demonstrated a 10 μm radius SWGMR that can provide a quality factor up to 45,000. Compared to SWGMRs built with conventional rectangular silicon pillars, the quality factors is increased by 4.6 times from a 5 μm radius SWGMR and 3 times from a 10 μm SWGMR radius, respectively.

Keywords: Subwavelength structures, Subwavelength grating waveguide, Micro-ring resonator

1. INTRODUCTION
In recent decades, photonic devices on silicon-on-insulator (SOI) platform have attracted intensive research interest due to the advantageous compact dimensions and high-volume manufacturability [1-5]. Particularly, micro-ring resonators on the SOI platform have been considered as a basic building block for a vast range of applications [6]. Numerous devices based on micro-ring resonators such as filters [7-10], switches [11-15], modulators [16-19], and sensors [20-23] have been demonstrated. However, the conventional strip waveguide based micro-ring resonators suffer from the intrinsic dilemma in having both high light confinement and strong light-matter interaction with environment. Specifically, a high confinement of light that ensures the desired low loss propagation also suggests limited light-matter interaction, which jeopardizes its performance. Recently, subwavelength grating (SWG) waveguides, comprised of periodically interleaved high and low refractive index materials with a pitch less than one wavelength, have been demonstrated as a promising solution to the aforementioned dilemmatic difficulties [24-28]. For SWG waveguides built on SOI wafers, the ratio of

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silicon and cladding materials can be engineered microscopically to achieve desired macroscopic properties. The control of these properties could potentially lead to significant performance improvement compared with conventional micro-ring resonators based photonic devices, such as filters [29] and sensors [30]. However, the reported SWG waveguide based micro-ring resonators (SWGMR) can only provide a moderate quality factor (~5600) with a large micro-ring radius of 15 μm [30], with which it is difficult to build practical compact silicon photonics devices. To achieve an HQ-SWGMR, it is essential to reduce the intrinsic bend loss of an unloaded SWGMR. In this paper, we applied our geometrical tuning art using trapezoidal silicon pillars instead of conventional rectangular silicon pillars [31] to reduce the bend loss of SWGMRs and successfully achieved desired HQ-SWGMRs by design.

2. DESIGN AND OPTIMIZATION

The 3D schematic of a conventional rectangular SWG waveguide is shown in Fig. 1(a), where \( A \) is the period of the SWG structure. \( l, w, \) and \( h \) are the length, width, and height of silicon pillars, respectively. SU-8 \( (n=1.58) \) is selected as the top cladding material. The period \( A \) is 300 nm and a typical silicon pillar with a geometry of \( l \times w \times h = 150 \text{ nm} \times 500 \text{ nm} \times 250 \text{ nm} \) has been selected. Quasi-TE polarization is investigated in this paper while the results can also be applied to Quasi-TM polarization. The schematic of an SWGMR built with trapezoidal silicon pillars (T-SWGMR) is shown in Fig. 1(b), where \( r \) and \( g \) denote the radius of the SWGMR and the center-to-center distance between the SWG bus waveguide and the curved SWG waveguide, respectively. Compared to conventional SWGMR fully built with rectangular silicon pillars (R-SWGMR), the SWGMR of a T-SWGMR will be built with trapezoidal silicon pillars to reduce bend loss while the SWG bus waveguide is still built with rectangular silicon pillars with the aforementioned geometry.

![3D schematic of a typical SWG waveguide](a)

![Schematic of a typical T-SWGMR](b)

Fig. 1. (a) 3D schematic of a typical SWG waveguide (b) Schematic of a typical T-SWGMR

To achieve the T-SWGMR with the highest quality factor, the top and bottom base of trapezoidal silicon pillars need to be optimally tuned to minimize the bend loss. FullWAVE™ (developed by Synopsys Inc.), a 3D finite-difference time-domain method (FDTD) numerical simulator, has been adopted for optimization. The results are summarized in the contour plot shown in Fig. 2(a).
It is found that a trapezoidal silicon pillar with 140 nm top base and 210 nm bottom base offers a minimum loss of 0.192 dB per 90° bend. It is 50.1% of the loss of an SWG waveguide bend built with conventional rectangular silicon pillars (0.383 dB per 90° bend). The top view of the optical fields (Re[Hz]) of 90° SWG waveguide bends with 5 μm radius are shown in Fig. 2(b) (conventional rectangular silicon pillars) and Fig. 2(c) (optimally tuned trapezoidal silicon pillars). One can readily find that the optical field of the SWG waveguide bend built with optimally tuned trapezoidal silicon pillars is better confined in the waveguide region (Fig. 2(b)) compared to the SWG waveguide bend built with conventional rectangular pillars (Fig. 2(c)). To validate that the coupling between SWGMR built with trapezoidal silicon pillars and SWG bus waveguide built with rectangular silicon pillars can be successfully triggered in a T-SWGMR, we simulated T-SWGMRs with various $g$ values through 3D FDTD. Fig. 3(a) shows a typical simulated transmission spectrum of a T-SWGMR ($r=5$ μm and $g=800$ nm) and Fig. 3(b) shows a typical top view of the simulated optical field (Re[Hz]) of this T-SWGMR on resonance ($r=5$ μm and $g=800$ nm). One can find the FSR increases when the wavelength increases with a slope of 67 pm/nm. The dispersion of group refractive index implies a dispersion of effective index of the bend modes in SWGMRs, which can be exploited to design sensors based on the dispersive critical coupling condition[32].
3. EXPERIMENTAL DEMONSTRATION

We design our 5 μm radius T-SWGMRs based on the aforementioned optimally tuned trapezoidal silicon pillars with 140 nm top base and 210 nm bottom base. To compare with other groups' results, 10 μm radius T-SWGMRs are also designed. A control group of 5 μm radius and 10 μm radius R-SWGMRs are also prepared for internal comparison. The four types of SWGMRs (5 μm radius T-SWGMR, 5 μm radius R-SWGMR, 10 μm radius T-SWGMR and 10 μm radius R-SWGMR) have been fabricated for experimental demonstration. The devices are fabricated on an SOI wafer (SOITEC) consisting of a 250 nm thick top silicon layer and a 3 μm thick buried oxide layer. All structures are patterned in a single E-beam lithography (JEOL 6000 FSE) step at the nanofabrication facility center at the University of Texas at Austin. The patterns are then transferred into the silicon layer through reactive-ion-etching (PlasmaTherm 790). SU-8 2005 (MicroChem Corp.) is spin-coated at 3000 rpm to form a 5 μm thick top cladding. An overnight baking at 80°C is applied to reflow the SU-8 for a tough infiltration [33]. Fig. 4(a) and 4(b) show typical SEM images of 5 μm radius R-SWGMR and T-SWGMR, respectively. Fig. 4(c) shows the typical high magnification SEM image of the coupling region between the bus waveguide and the micro-ring of a 5 μm radius T-SWGMR.

![Fig. 4. (a) SEM image of 5 μm radius R-SWGMR. (b) SEM image of 5 μm radius T-SWGMR. (c) High magnification SEM image of the coupler of a 5 μm T-SWGMR.](image_url)

After spin-coating the SU-8 cladding, the devices are tested in a customized grating coupler alignment system shown in Fig. 5(a). Two xyz stages are used to align the fibers to on-chip grating couplers and a camera mounted on another xyz stage is tilted at 45° angle to visually assist in the alignment. Light from a broadband amplified spontaneous emission (ASE) source (1510 nm–1630 nm) is input to the device through a polarization maintaining fiber mounted on a tilting stage. After passing through the devices, light signal is collected by the output fiber, which is fed to an optical spectrum analyzer (OSA) to record the optical spectra. Fig. 5(b) and 5(c) show the transmission spectra of the four types of SWGMRs around the resonance of the highest quality factor. The 5 μm radius T-SWGMR can offer a resonance peak with a quality factor as high as 11,500, which 4.6 times to highest quality factor (~2,800) resonance peak that a 5 μm
radius R-SWGMR can offer. For 10 μm cases, a T-SWGMR can offer a resonance peak with a quality factor as high as 45,000, which is 3 times to highest quality factor (~15,000) resonance peak that a 10 μm radius R-SWGMR can offer.

Fig. 5. (a) Grating coupler alignment system. (1) xyz stage, (2) Fiber mounts on tilting stage, (3) Input polarization maintaining fiber, (4) Output single mode fiber, (5) 45° tilted camera, (6) Adjustable sample stage. Transmission spectra of (b) 5 μm radius T-SWGMRs and R-SWGMRs, and (c) 10 μm radius T-SWGMRs and R-SWGMRs.

4. CONCLUSION

In conclusion, we successfully implemented our geometrical tuning art into HQ-SWGMRs. We demonstrated the smallest SWGMR (T-SWGMR architecture) with an applicable quality factor as high as 11,500. The quality factor can be increased to 45,000 for a 10 μm SWGMR (T-SWGMR architecture). Compared to the results reported earlier, where a quality factor of ~8,800 was obtained from 10 μm radius SWGMR (R-SWGMR architecture) [29], we successfully increase quality factor by five times. This study offers a promising platform for light-matter interaction research.

REFERENCES


