Modeling and analysis of silicon-on-insulator elliptical microring resonators for future high-density integrated photonic circuits*

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We propose a novel resonator containing an elliptical microring based on a silicon-on-insulator platform. Simulations using the three-dimensional finite-difference time-domain method show that the novel elliptical microring can efficiently enhance the mode coupling between straight bus waveguides and resonator waveguides or between adjacent resonators while preserving relatively high intrinsic quality factors with large free spectral range. The proposed resonator would be an alternative choice for future high-density integrated photonic circuits.

Keywords: elliptical microring resonator, silicon-on-insulator, mode coupling, intrinsic quality factor

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1. Introduction

Silicon-on-insulator (SOI) has become an attractive platform for on-chip photonic integrated circuits due to its compatibility with standard complementary metal-oxide-semiconductor (CMOS) technology, high density integration with microelectronic integrated circuits, and low loss.[1] The high-index-contrast of the SOI platform allows a strong confinement of light in the waveguide, enabling compact optical devices with small bending radii. SOI optical microring resonators (MRRs) are key building blocks for very large scale integrated (VLSI) optical circuits, which have applications in many functional optical devices, such as add-drop filters, lasers, modulators, switches, and delay lines.[2−8] To implement optical devices, compact and low-loss MRRs are universally required to achieve a large free spectral range (FSR), high integration density, and low power consumption. Most of these MRRs are conventional circular and racetrack MRRs. Since some resonator applications require wide bandwidths and alleviate fabrication limitations, the mode coupling between the bus waveguide and the resonator waveguide or between adjacent MRRs needs to be enhanced. For circular MRRs, in order to enhance the mode coupling between the straight bus waveguide and the resonator waveguide or between adjacent resonators, very narrow gap widths are required. However, narrow gaps are difficult to fabricate and to control precisely, which would reduce the intrinsic Q factors of the resonators due to the optical coupling loss.[9] Especially, these issues are extremely serious for ultra-compact MRRs with small bends (several microns). To alleviate these issues and further improve the mode coupling, two main methods have been proposed in previous literatures.[10] One method uses a curved bus waveguide to laterally couple circular MRRs instead of the conventional straight bus waveguide,[11] and the other one stretches the coupling point of circular MRRs to a straight waveguide to form racetrack MRRs. However, the former approach is no help for enhancing the mode coupling between adjacent resonators, which is often useful for high-order MRRs to achieve better resonance performance. The latter one dramatically increases the intrinsic loss of the resonator due to the mode mismatch between the straight and bent portions of racetrack MRRs. Moreover, the extra straight part in the racetrack MRR increases the perimeter of the resonator, reducing the FSR of the resonator. Therefore, a new

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kind of MRR with an optimized shape which can provide both strong mode coupling and low intrinsic loss with a large FSR (small bend) availability is needed for various optical devices.

In this paper, we propose a novel resonator with an elliptical microring as an alternative solution to alleviate the above limits, which is naturally termed as elliptical MRRs here. Figure 1 shows the schematic of a waveguide-to-resonator coupling scheme containing a straight bus waveguide coupling with a typical elliptical MRR with a major radius b in the horizontal direction and a minor radius a in the vertical direction. Compared with the circular MRR, the elliptical MRR provides stronger mode coupling between a straight bus waveguide and an elliptical MRR or adjacent elliptical MRRs by flattening the sharp bend of circular MRR in the coupling area. Compared with the racetrack MRR, the elliptical MRR alleviates the mode mismatch in the racetrack by using gradient arc connections of the bent waveguides in the resonator, which is different from the straight and bent waveguide junctions in the racetrack MRR, preserving a relatively low intrinsic loss. These unique characteristics of the novel resonator proposed here are helpful for applications of SOI MRRs to realize both strong coupling and low intrinsic loss with a compact size. The novel elliptical MRR can provide a new choice for building blocks in future integrated photonic circuits.

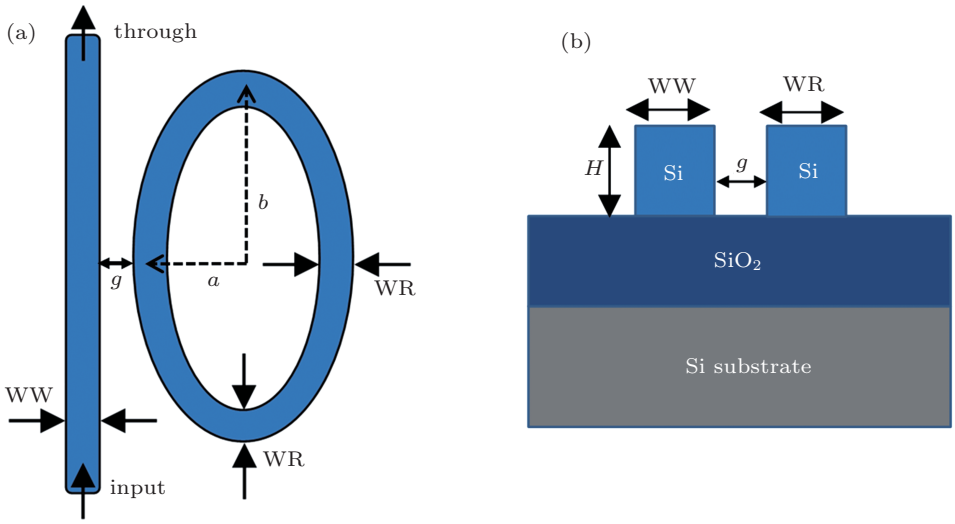


Fig. 1. (colour online) Schematic diagram of: (a) top view of an elliptical MRR laterally coupled to a straight bus waveguide; and (b) cross-section view at the coupling region. WW: waveguide width, WR: resonator width, a: minor radius, b: major radius, g: gap width, H: silicon height.

2. Coupling to the microring resonators

For optical MRR devices, the rate of energy coupling into and out of the MRRs is a crucial criterion for the performance of optical MRRs. We employ the coupled mode theory presented in previous literatures.[12−15] for a universal analysis of the mode coupling between two waveguides in close proximity. The coupling coefficient κ can be expressed as

$$\kappa = -\frac{\mathrm{j}\omega\varepsilon_0}{4}\int \mathrm{d}z \iint \mathrm{d}x\mathrm{d}y(n_1^2 - n_0^2)E_1^*(x,y) \times E_2(x,y)\,\mathrm{e}^{-\mathrm{j}(\beta_1-\beta_2)z}, \quad (1)$$

where ω is the circular frequency, ε_0 is the permittivity of free space, the subscripts 1 and 2 represent the two coupled waveguides (for the coupling scheme in Fig. 1, the waveguides 1 and 2 are the straight bus waveguide and the resonator waveguide, respectively), β and $E(x,y)$ are the propagation constant and the mode field of the waveguide, n_1 and n_0 are the refractive indexes of the waveguide 1 and its cladding material, $\mathrm{d}x\mathrm{d}y$ is the differential element of the waveguide cross section area, and the z axis is along the propagation direction.

For the given SOI platform, equation (1) shows that the coupling coefficient κ is mainly dependent on three factors in the integral: mode field overlap ($\iint \mathrm{d}x\mathrm{d}yE_1^*(x,y)E_2(x,y)$), interaction length ($\int \mathrm{d}z$), and phase matching ($\exp[-\mathrm{j}(\beta_1-\beta_2)z]$). In order to obtain strong mode coupling, the optimization on the above three factors should be considered: 1) reduce the size (width and height) of the waveguide or increase the slab height of the waveguide to alleviate

the confinement of light in the waveguide, i.e., to increase the mode field overlap;[16] 2) reduce the gap width between two coupled waveguides to increase the mode field overlap, usually the mode coupling increases exponentially as the gap width decreases;[2] 3) increase the interaction length between two coupled waveguides;[17] 4) decrease the phase mismatch between two coupled waveguide modes.[16] Therefore, to optimize all or any of the above three factors, the resonator and other waveguide device architecture can obtain strong mode coupling.

In order to further quantitatively investigate the coupling strength of the elliptical MRRs, a commercial three-dimensional (3D) finite-difference time-domain (FDTD) numerical simulation tool.[18] is employed. Figures 2 and 3 show the simulation results for the power coupling κ^2 of different elliptical MRRs between bus straight waveguides and elliptical MRRs and between coupled elliptical MRRs, respectively. The two coupling schemes are shown in the insets of Figs. 2 and 3. In the simulation, different elliptical MRRs with the same perimeters are chosen to quantitatively compare the coupling strength between the MRRs and the straight bus waveguides or coupled MRRs, where the circular MRR can be seen as a special elliptical MRR whose major radius b and minor radius a are equivalent. In order to ensure a large FSR over 30 nm (covering the entire communication band supported by erbium-doped optical fiber amplifier), the radius of a circular MRR is designed to be 2.5 μm, so that the perimeters of all these elliptical MRRs are 5π μm. The minor radius a of these elliptical MRRs is chosen in a range from 1 to 2.5 μm (circular MRR) with an increment of 0.1 μm, while the corresponding major radius b is determined by a good approximate formula of the ellipse's perimeter[19]

$$P = \pi(a+b)\left[1+3\left(\frac{a-b}{a+b}\right)^2\right] \times\left[\left(10+\sqrt{4-3\left(\frac{a-b}{a+b}\right)^2}\right)\right]^{-1}, \quad (2)$$

The gap widths between the straight bus waveguides and the resonator waveguides are fixed at an appropriate size of 200 nm, and they vary from 100 to 400 nm with an increment of 100 nm between coupled elliptical MRRs. To simplify the analysis, both the straight waveguides and the curved waveguides have the same rectangular cross section of 300 nm×340 nm, and the wavelength of the light is 1.55 μm. The input field has a quasi-TM polarization and is launched relatively far from the coupling region.

It can be easily seen that the elliptical MRRs provide stronger power coupling than the circular MRRs with the same perimeter. In mathematics, the curvature radii of elliptical MRRs are larger in the coupling region than those of the circular MRR, which can be intuitively seen in the insets of Figs. 2 and 3. Hence, the equivalent radii of the elliptical MRRs in the coupling region are larger than those of the circular MRR, i.e., there have a longer interaction length, a smaller average gap width, and better phase matching in the coupling region. Moreover, the smaller the minor radius a is, the stronger the power coupling κ^2 is, which is because that an elliptical MRR with a smaller minor radius a is flatter in the horizontal direction and longer in the vertical direction, i.e., it has a larger equivalent radius in the coupling region. As seen in Fig. 2, even with a minor radius a of about 2.5 μm (close to that of circular MRR), the power coupling of elliptical MRRs increases to more than twice that of circular MRRs. Therefore, to optimize the elliptical microring (major radius b and minor radius a) of the novel resonators in a fixed perimeter, strong mode coupling can be obtained to exploit some unique and excellent physical properties of the proposed elliptical MRRs.

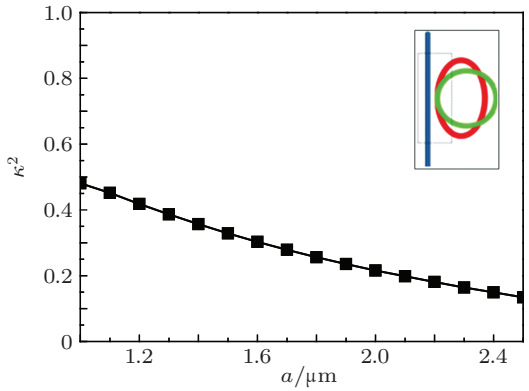


Fig. 2. (colour online) Power coupling κ^2 between the bus straight waveguide and the resonator waveguide versus the minor radius a.

The racetrack MRR also can provide strong mode coupling due to its large interaction length, small average gap width, and minimal mode mismatch. It can enhance the power coupling κ^2 to about 0.7 with π–μm long straight waveguide and 1.5-μm radius bent waveguide. However, the intrinsic Q of the resonator dramatically drops to about 3000 (circular MRR to about 10^5). This result will be discussed in detail be-

low.

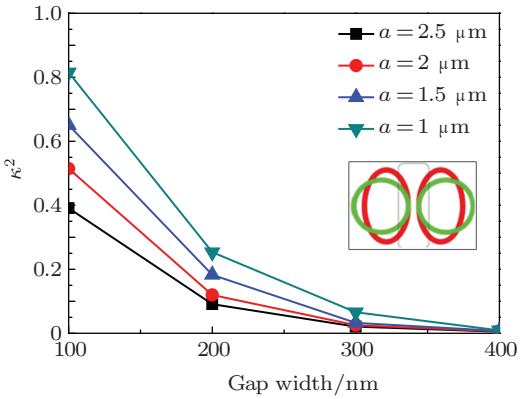


Fig. 3. (colour online) Power coupling κ^2 between coupled elliptical MRRs versus the gap width.

3. Intrinsic Q of the microring resonator

The quality factor Q is another important criterion for the performance of MRRs. It is defined as the product of the ratio of the stored energy in the resonator to the power lost out of the resonator and the angular resonance frequency. Only the quality factor caused by the radiation loss is called the radiation Q or the intrinsic Q ($Q_{\rm i}$ is the quality factor when the resonator is isolated and not coupled to any other waveguide devices), so that it is an important figure of merit for the intrinsic loss of MRRs. Consider a MRR of add-drop type with an input bus waveguide and an output bus waveguide, the drop port response of the device is given by

$$|\Gamma_{\rm d}|^2 = \frac{\gamma k_1^2 k_2^2}{1 - 2\gamma t_1 t_2 \cos(\Delta\omega T) + (\gamma t_1 t_2)^2},$$
$$T = \frac{n_{\rm g} L}{c}, \quad r_{\rm FS} = \frac{\lambda_0^2}{n_{\rm g} L}, \tag{3}$$

where κ_i and t_i ($\kappa_i^2 + t_i^2 = 1$ for lossless coupling) are respectively the coupling coefficient and the transmission coefficient, the subscripts 1 and 2 represent the input and output bus waveguide-resonator couplers, $\Delta\omega$ is the frequency detune from the angular resonance frequency, γ is the round-trip attenuation coefficient, T is the round-trip time traveling in the resonator, L is the round-trip optical path in the resonator, $r_{\rm FS}$ denotes the free spectral range, and n_g and λ_0 are the group index and the resonant wavelength of the resonator, respectively. When $|\Gamma_{\rm d}|^2 = |\Gamma_{\rm d}|^2_{\rm max}/2$, we can obtain the full width at half maximum (FWHM) $2\Delta\omega$ by using the Fourier series expansion from Eq. (3). Hence, the intrinsic Q ($k_i = 0$, $t_i = 1$) can be deducted as

$$Q_i = \frac{\omega_0}{2\Delta\omega} = \frac{\pi\lambda_0}{r_{\rm FS}} \frac{\sqrt{\gamma}}{1-\gamma}, \tag{4}$$

From Eq. (4), we can find that the intrinsic Q is related to FSR and attenuation coefficient γ. However, the intrinsic Q is not inversely proportional to the FSR, because when the FSR decreases, usually the bending radius decreases and the radiation loss dramatically increases. For the given SOI system, silicon has a high index contrast relative to silica (or air), so that the optical power can be tightly confined in the waveguide. As a result, the radiation loss of bent waveguides can be neglected at large bending radii (> 5 μm). However, the optical modes in bent waveguides with small radii are always obvious leaky modes, the intrinsic Q (or bending loss) will dramatically decrease (or increases) when the radius of waveguide bend decreases. As seen in Fig. 4 derived from a 3D FDTD simulation, the radii of circular MRRs vary from 0.5 to 2.5 μm with an increment of 0.5 μm, the intrinsic Q factor increases nearly from 10^2 to 10^5 and the bending loss decreases nearly from 10^3 to < 10 dB/cm, respectively. In the intrinsic Q simulation of the MRRs, the same simulation parameters are selected as the above coupling simulation.

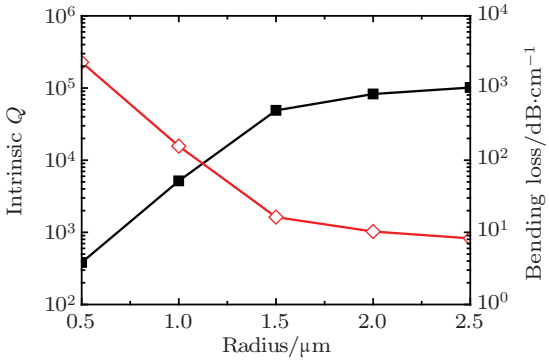


Fig. 4. (colour online) Intrinsic Q and bending loss versus the bending radius of circular MRRs.

Three kinds of MRR (racetrack, circular, and elliptical) with the same parameters as the aforementioned coupling simulation are chosen to quantitatively compare their intrinsic Q and bending loss via 3D FDTD simulation. For the comparison of racetrack MRRs and circular MRRs, the resonators would dramatically reduce the intrinsic Q because of the large mode mismatch between the straight and bent portions of racetrack, especially with very small bending radii. As shown in Fig. 5, the intrinsic Q of racetrack MRRs varies from about 1.3×10^4 to about

3×10^3 when the coupling length in the straight portions of the racetrack MRRs is chosen to be $\pi/4$, $\pi/2$, $3\pi/4$, and π μm. Correspondingly, the bending radius in the bent portions of the MRRs decreases from 2.25 to 1.5 μm to maintain the same perimeter of 5π μm, but the loss in the resonator does not increase significantly. This is because the loss of racetrack MRRs is more correlative to the large mode mismatch between the straight and bent portions of the resonators (transmission attenuation in the junctions between the straight waveguide and the bent waveguide four times a round-trip) than they are to the radiation loss in the bent sections of the resonators. Hence, realizing a large FSR while preserving a high intrinsic Q is very challenging for racetrack MRRs.

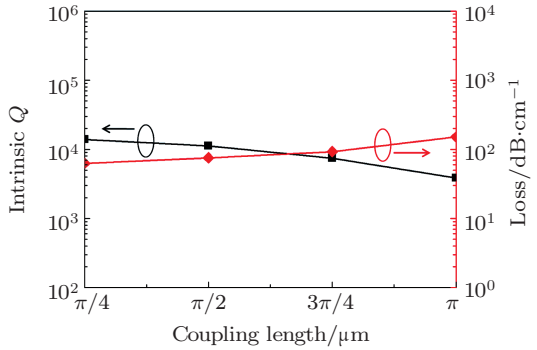


Fig. 5. (colour online) Intrinsic Q and loss versus the coupling length of racetrack MRRs.

The elliptical MRRs can efficiently alleviate the mode mismatch loss due to their seamless links of the bent waveguides with gradually changed curvature radii. Figure 6 shows the simulated intrinsic Q and the bending loss of elliptical MRRs with different shapes (major radius b and minor radius a). It can be easily seen that the intrinsic Q varies greatly. When the minor radius a is closer to 2.5 μm (close to that of circular MRRs), the intrinsic Q (bending loss) is much higher (lower). When the a is increasingly different from 2.5 μm, the intrinsic Q (bending loss) is much lower (higher). There are two reasons for this: (i) the curvature radii in the sharp bent portions of elliptical MRRs are very small especially when the a is far away from 2.5 μm (e.g. $a = 1$ μm, the smallest curvature radius is about 0.25 μm), the ultra-sharp bends would induce tremendous radiation loss and significantly deteriorate the intrinsic Q of the resonators; (ii) the curvature radii in the elliptical MRRs change greatly from the largest curvature radius to the smallest curvature radius, leading to a relatively large mode mismatch loss. Figure 6 indicates that the elliptical MRRs without aggressively changed bent waveguides can guarantee relatively high intrinsic Q.

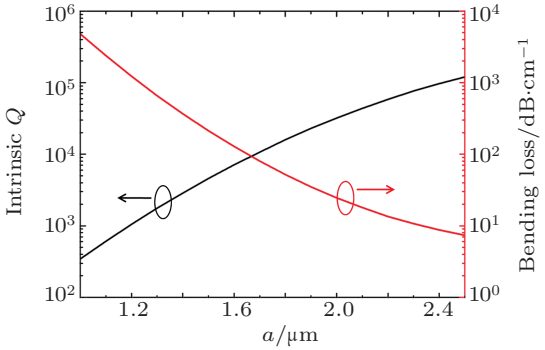


Fig. 6. (colour online) Intrinsic Q and bending loss versus the minor radius a of elliptical MRRs.

In addition, elliptical MRRs (including circular MRRs) can be designed and fabricated with an asymmetric coupler design (wider resonator waveguide) to achieve a higher Q and stronger mode coupling.[20] However, for racetrack MRRs with an asymmetric coupler design, phase mismatch between the asymmetric straight waveguides would dramatically reduce the mode coupling because of the long integral length. Therefore, the elliptical MRRs exhibit much more advantages in the tradeoff of strong coupling and high intrinsic$Q$ than other MRRs.

4. Conclusion

In conclusion, we have proposed a novel elliptical MRR based on an SOI platform. The proposed elliptical MRRs can efficiently enhance mode coupling while preserving a relatively high intrinsic Q with a large FSR. It is believed that the novel resonators of different elliptical shapes and different sizes deserve further theoretical and experiment research, and that they will be a new choice for building blocks in future integrated photonic circuits.

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