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Q-enhanced racetrack microresonators

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ABSTRACT

A Q-enhancement strategy for racetrack microresonators is put forward. The design is based on the modification of the resonator geometry in order to mitigate the two main sources of radiation loss in the presence of curved waveguides: the discontinuities at the junctions between straight waveguides and the bent sections, and the continuous loss at the curved waveguide sectors. At the same time, the modifications of the geometry do not affect the versatility of coupling of racetrack resonators in integrated optical circuits, which is their main advantage over ring microresonators. The proposal is applied to the design of high-Q racetrack resonators for the silicon nitride CMOS-compatible platform having bent radii amenable for large-scale photonic integration. Numerical calculations show over 100% improvement of the Q factor in Si_3N_4/SiO_2 resonators.

1. Introduction

Racetrack and ring microresonators are highly versatile elements within integrated photonics with applications as add-drop multiplexers [1], optical filters [2], optical switches [3], sensors [4], modulators [5], or in slow light systems based on coupled resonator waveguides [6]. These microresonators can be implemented in a variety of optical integration platforms: silicon on insulator (SOI) [7], silica on silicon [8], polymer [9], Si_3N_4/SiO_2 [10], GaAs/AlGaAs [11], or InP/InGaAsP [12].

A key parameter characterizing the performance of a resonator is the quality factor Q [12]. In the time domain, the Q-factor of a resonant mode is determined by the $1/e$ decay time of the electromagnetic energy stored in that mode. In the frequency domain, it is equivalently characterized by the sharpness of the resonance relative to its central frequency. Its value depends on the total loss, including both the effects due to coupling to an external circuit and those associated to the propagation in the ring. In the absence of external coupling, the intrinsic Q-factor is called the unloaded Q of the resonator. The coupling of the microresonator to an external waveguide modifies the resonator Q to its loaded value Q_L. Although in certain applications, such as optical delay lines, a low value of Q_L is usually desirable to increase the transmission bandwidth [13], any reduction of the intrinsic Q in this cases results in performance degradation and high values of the unloaded Q, limited by the radiation and/or transmission losses, are most typically advantageous.

There are various contributions to the round-trip loss in an unloaded resonator: the intrinsic propagation loss of the waveguide material, the effect of the roughness of the waveguide walls or the effects due to the bending in the curved waveguide sections. In high contrast integrated optics platforms, the effect of bending can be negligible even for very small radii of curvature. Such is the case in SOI photonic circuits. In this platform, on the other hand, the intrinsic propagation losses are relatively high. The converse situation is found, for instance, in Si_3N_4/SiO_2 integrated circuits, where intrinsic losses are very small, but the reduced waveguide core/cladding refractive index contrast relative to that of SOI can result in higher values of the radiation loss due to waveguide curvature.

Ring microresonators offer higher values of Q when compared with racetrack microresonators. For a fixed FSR, the bending radius is larger in the ring configuration, which is also free from the discontinuities at the junctions between the straight and curved sections. Nevertheless, the straight sections in the racetrack geometry permit a more accurate control of the coupling to external waveguides that is limited by the fabrication tolerances. This often makes the racetrack arrangement the preferred option [14].

A pulley type configuration, with the coupling bus waveguide surrounding the resonator, has been shown to reduce the radiation loss and to provide very high Q factors when used in microdisk [15,16] and microring [17] resonators, even though improvements have been more elusive in the case of racetrack microresonators [17].

In the pulley geometry, the bus waveguide is a design element both of the resonator and the coupling system, resulting a largely restrictive configuration. In this work, we exploit the radiation quenching properties of the external slab in pulley resonators but with independence to the coupling of the resonator. This is supplemented with the lateral

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offset [18] technique to reduce the loss due to the transition from the straight to the bent transmission section, which had been previously addressed for GaAs-AlGaAs resonators [19]. The resulting geometry is shown to provide large improvements in the Q factors of racetrack microresonators. This is particularly interesting when the radiation loss can dominate the intrinsic propagation loss, as it is the case in silicon nitride photonic integrated circuits. At the same time, the versatility of racetrack microresonators as key design elements of integrated optical circuits is kept intact, since the geometry modifications affect at the resonator itself and not the essential coupling properties to the optical circuit.

2. The silicon nitride platform: device fabrication considerations

The photonic integration platforms that exploit the broadly established complementary metal-oxide-semiconductor (CMOS) infrastructure are particularly appealing. Among them, the silicon-on-insulator (SOI) [7] is the most developed one, and has footed the development of an incipient silicon photonics industry. Large scale photonic integration is facilitated by the large index contrast of SOI waveguides. Nevertheless, other limiting factors, such as two-photon absorption, affect nonlinear photonic applications. Silicon nitride is an emerging CMOS-compatible alternative to SOI photonics. Even though the refractive index contrast is smaller than that of SOI, it offers reduced intrinsic linear [20] and nonlinear losses [21]. Very small linear losses are very interesting, for instance, for quantum applications operating at the single-photon level [22]. Low nonlinear losses, on the other hand, are very appealing for nonlinear photonics applications [21]. Further applications of the silicon nitride platform include coherence tomography [23] or lab-on-a-chip devices [24,25].

We will assume a typical Si_3N_4/SiO_2 channel waveguide geometry as shown in Fig. 1. In order to obtain high optical quality deposited films, the silicon nitride layer height h is limited to values of $h < 400$ nm due to film stress. Catastrophic cracking occurs at thicker layers, severely limiting device performance [26]. Extremely thin silicon nitride films [27] avoid stress issues. More sophisticated fabrication processes, for instance, with the introduction of mechanical trenches for isolating photonic devices from propagating cracks [26], permit to grow thicker ($h > 400$ nm) Si_3N_4 layers with better confined optical modes and smaller radiation losses.

Ultra-high Q silicon nitride ring microresonators with very thin Si_3N_4 layers have highly delocalized modes and require bend radii in the millimeter range [27]. Even for thick Si_3N_4 films with improved mode confinement, ring radii are still over one hundred microns [26]. This contrasts with high-Q silicon ring microresonators that can have radii comparable to the optical wavelength in vacuum [28]. Large rings not only hinder large scale integration, but the corresponding reduction in the free spectral range can also impose a severe limitation for certain applications. As discussed below, one of the radiation quenching geometry modifications can also be applied to ring microresonators, even though this work focuses specifically on the racetrack geometry.

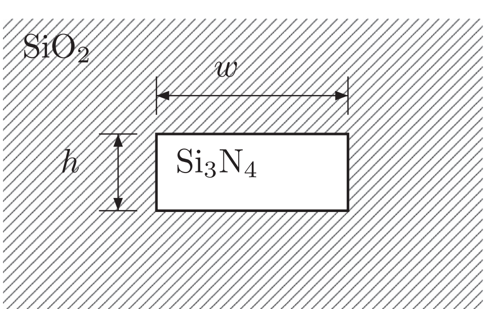

Fig. 1. Channel waveguide geometry used for the numerical calculations.

In the design of complex integrated photonic circuits, racetrack microresonators offer superior versatility over ring microresonators due to the better control of the coupling coefficients to the external optical circuitry, but they suffer from increased radiation losses due to the transitions of straight to bent waveguide sections. In this work, we will seek practical values of the bent radii of the racetrack resonators compatible with large scale integration in the silicon nitride platform by the implementation of mitigation measures for the sources of radiation loss.

We will assume an intermediate channel waveguide geometry (similar, for instance, to that of [29]), with relatively high mode confinement within the film stress limits. The parameters assumed are $w = 1$ μm and $h = 300$ nm. The refractive indices of silica and silicon nitride have been taken as 1.4501 and 1.9792, respectively. With these parameters, the devices support both quasi-TE and quasi-TM polarized modes, but coupling between the two polarizations is expected to be negligible [26]. In the analysis, we will focus on the lowest order quasi-TE polarized mode.

In the fabrication process, there is a deviation between the actual waveguide width and the waveguide within the mask layout; the so-called underetch. This deviation is due to mask erosion and the etching processes, but its effect can be handled automatically in the mask layout by the rendering software. Besides the underetch, there is also a variation in the waveguide width across the wafer due to the lithography process. The waveguide-width tolerance across the wafer can be typically of 100 nm.

3. Proposed scheme

There exist two main and independent radiation loss mechanisms associated with the propagation in curved waveguides [30–32]. The first one is the coupling mismatch existing between the optical mode field in the straight waveguide section and that of a curved waveguide with constant curvature. The second one is the continuous radiation loss of the modal field in the curved transmission sections.

Since these two sources of radiation loss have clearly distinct physical origin, they are addressed independently in the proposed scheme and any possible correlation effect in the geometry modifications is neglected at the design stage. The losses at the waveguide transitions are dealt with using the lateral offset technique [18]. For the radiation of the bent sections, the intrinsic radiation quenching mechanisms of pulley resonators [17] is adopted. With an adequate design, the waveguide around the resonator in a pulley configuration has the effect of reducing the radiation loss when the modes in the inner and outer coupled structures are phase mismatched. This is similar to the result of phase mismatch in asymmetric couplers [33], where the coupler supermodes do not have the typical even and odd distributions of symmetric couplers, but are mainly localized at one of the guides and evanescent at the other. For a bent guiding structure the presence of a nonsynchronous parallel curved slab has the effect of reducing the radiation loss [17].

The conventional geometry of a racetrack microresonator is shown in Fig. 2 (a). This geometry is fully defined by the waveguide width w, the radius of the bent sections R and the length of the straight sections L_s. It can be compared with the proposed scheme in Fig. 2 (b). The modifications include a lateral shift l_{off} of the straight waveguides and the existence of radiation quenching curved exterior sectors of width w_e and inner radius of curvature R_e. The nonsynchronous condition of the curved coupler will require that either $w_e < w$ or $w_e > w$. The angular extent of the exterior sectors is limited by the angular parameters θ_l, l=1,2, that are intended to be adjusted to permit the coupling of the resonator to other structures either from one side or both sides. Large values of θ_l are suboptimal in relation with the maximal reduction in the radiation loss. This effect is studied in the following section.

The effect of the geometry modifications on the radiation patterns