Design and Characterization of Q-enhanced Silicon Nitride Racetrack Micro-Resonators

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Abstract

Q-enhanced racetrack micro-resonators for the silicon nitride photonics integration platform have been designed, fabricated and characterized. The proposed geometries permit to mitigate the impact of radiation loss at curved waveguides, one of the major limitations of silicon nitride circuits, therefore providing an increase of the intrinsic Q factor of micro-resonators when compared with the conventional structures with the same bent radii. The schemes put forward in this work permit a reduction of the size of the devices that has a direct impact on the integration scale in this platform. When used in the curved sections of waveguides routing optical signals within an integrated photonic circuit, these geometries provide a reduction of the radiation loss and permit the use of smaller bent radii and to increase the circuit integration density.

1 Introduction

Racetrack microresonators are key building blocks in the different photonic integration platforms [1]. They permit to implement add-drop multiplexers [2], optical filters [3–4], optical switches [5], sensors [6], modulators [7], and
they are the constituent elements of slow and fast light systems based on coupled resonator waveguides [8, 9].

Irrespective of the particular application, the behavior of a micro-resonator in an optical system is defined by its Q-factor, which is built from two distinct contributions: one is the coupling to the external circuit, which is design-specific, and the other is due to the internal loss that define the unloaded or intrinsic Q-factor. In general, high unloaded Q-factor or, equivalently, low loss is a desirable property in any implementation.

Propagation loss in the resonator can have various origins: the intrinsic loss of the waveguide material, the effect of the roughness of the waveguide walls or the curving of waveguide sections. The impact of each loss mechanism depends on the specific platform. In silicon on insulator (SOI) photonic circuits, the effect of bending can be negligible even for very small radii of curvature because of the highly confining high index contrast silicon waveguides. Nevertheless, intrinsic propagation losses are relatively high in the SOI platform. The converse situation is found in Si$_3$N$_4$/SiO$_2$ photonic integrated circuits, with very small intrinsic losses and large radiation losses due to waveguide curvatures, for the same bent radii, due to the reduced waveguide core/cladding refractive index contrast.

In [10], a general approach for the Q enhancement of racetrack micro-resonators was proposed. This strategy acts on the two sources of optical loss due to waveguide bending in a racetrack micro-resonator. In the curved waveguide sections, the modal effective indices become complex [11] and field propagation is accompanied by the continuous production of a radiation wave. The second cause of loss is due to the discontinuities existing at the straight-bent sections that produce localized radiation beamed along the optical axis [10]. In the scheme of [10], the first effect is reduced with the aid of bent coupled asymmetric waveguide sections. This geometry modification is compatible with the conventional lateral offset technique [12] that is introduced at the discontinuities to mitigate the second source of radiation. These two combined counteractants permit to notably reduce the losses and enhance the Q-factor of racetrack microresonators in low-contrast integration platforms like silicon nitride, silica on silicon or polymer. In turn, this Q-enhancement allows the use of shorter bend radii, with a direct impact on the attainable integration density.

The 2D numerical calculations presented in [10] are adequate for a proof of concept analysis but lack the high accuracy required in the design of devices targeted for the fabrication of integrated circuits. In [13], a full vector 3D extension of the previous work was presented including the application of modal calculations [14, 15] that hold the high level of accuracy demanded by this problem. In this work, we present the results of the design and
Figure 1: A is the geometry of a conventional racetrack micro-resonator in an add-drop configuration. Case B incorporates radiation quenching coupled asymmetric curved waveguides and C also includes lateral offsets at the straight-bent discontinuities.

characterization of the racetrack geometries proposed in [10] fabricated in the silicon nitride platform.
Figure 2: Contours of $\log_{10}(n_i)$ for the quasi-mode localized at the interior waveguide. $R = 15 \ \mu m$, $R = 20 \ \mu m$, and $R = 25 \ \mu m$ for (a), (b), and (c) plots, respectively.

2 Q-enhanced racetrack microresonators

The geometries of the three fabricated structures are displayed in Fig. 1. Subplot A, shows a conventional racetrack geometry in an add-drop configuration, the geometry depicted in subplot B includes radiation-quenching curved asymmetric coupled sections and the design in C implements the former plus lateral offsets at the discontinuities.
In the schematics of Fig. 1, \( w \) is the waveguide width, \( L_c \) is the length of the straight sections of the racetrack micro-resonator, and \( R \) is the bend radius of the curved sections. The total ring length is given by \( L = 2(\pi R + L_s) \). The self-coupling coefficients of the evanescent couplers that connect the resonator to the external waveguides, which we will assume to be equal and of value \( r \), is determined by the effective coupler length, which depends on both \( L_c \) and the curvature of the access waveguides [10], and the gap \( g \) between the ring and access straight waveguides. Symmetric structures, with identical couplers in the upper and lower branches are assumed.

In an uniformly curved waveguide geometry of radius \( R \), the quasi-guided mode solutions can be described as \([13]\):

\[
\{E, H\} (\rho, \phi, z) = \{e, h\} (\rho, z) \exp(j\beta R\phi),
\]

where \((\rho, \phi, z)\) define a cylindrical coordinate system having \( \rho \) and \( z \) as the coordinates transverse to the propagation \([13]\). \( E \) and \( H \) are, respectively, the electric and magnetic field strengths, \( \{e, h\}(\rho, z) \) are the complex modal fields, \( R \) is the bend radius, and \( \beta \) is the complex propagation constant. The complex effective index of the modal field \( n = n_r + jn_i \) is related to the propagation constant as \( \beta = k(n_r + jn_i) \) with \( k = \omega/c \). These modal solutions continuously shed radiation as they propagate and the imaginary part of the complex effective index \( n_i \) accounts for the radiation loss \([11]\).

Radiation loss can be modified by adding an external waveguide section, as shown in Fig. 1 B and C. The radiation quenching properties of coupled asymmetric curved waveguides have been described in detail in \([13]\), using highly accurate 3D vector modal calculations, in terms of the variation of the properties of modes propagating in the structure as a function of the waveguide separation \( s \) and the width of the exterior waveguide \( w_e \) when the width of the main waveguide \( w \) is kept fixed and the radius of curvature \( R \) is varied. In the following paragraphs, we summarize some of the results of Ref. \([13]\).

We consider first a straight coupler. In the symmetrical case, \( w_e = w \), we have a modal degeneracy at \( s \to \infty \) with each mode occupying one of the cores of the well-separated and, therefore, uncoupled waveguides. As the two waveguides become closer, the degeneracy is broken due to mutual coupling with the result of a splitting of the propagation constants of the two super-modes. Two branches, with a separation that grows as \( s \) decreases, can be observed when the modal indices are plotted as a function of \( s \). These two branches correspond, respectively, to odd and even modal fields that have intensities evenly split between the two waveguide cores at small \( s \) in the symmetrical case. When the modal indices are evaluated over the whole
Table 1: Q enhancement factors for the three values of $R$ considered in this work and resonance frequencies distributed along the C band. $EF_{IJ}$ denotes the enhanced factor when the design is modified changing geometry I to geometry J.
Figure 3: Micorgraphs of the fabricated micro-resonators of type A and B (subfigures (a) and (b), respectively) for $R = 15 \, \mu m$.

In the $(w_e, s)$ plane, this splitting results in the creation of two sheets; the lower sheet corresponds to the odd mode and the upper sheet to the even mode. For $w_e > w$, the odd mode is predominantly localized at the main waveguide, while it is the even mode the one that is localized at the main waveguide for $w < w_e$ [13].

Curving the asymmetric coupler induces a shift of the effective degeneracy condition as the radius diminishes from $R \to \infty$ to a finite value [13]. For the small values of $R$ required in a photonic integrated circuit (PIC) design, it is the odd mode the one that is localized at the main (interior) waveguide for most values of $(s, w_e)$. By studying the radiation properties of this mode as parameters $w_e$ and $s$ are varied, one finds that the radiation loss described by the imaginary part of the modal effective index varies in a regular manner [13] that permits to select points in the $(s, w_e)$ plane that give designs with reduced radiation loss. This is the same type of variation that had been found in the 2D case using finite-differences time-domain (FDTD) calculations [10]. The change in the imaginary part of the effective modal index is accompanied by a change in the modal field distribution such that transverse intensity distribution is more localized at the waveguide when $n_i$ decreases and expands outwards in the transverse plane as $n_i$ increases.
Figure 4: Measured through and drop responses of the add-drop resonators at a resonance placed at the short wavelength end of the C band. (a), (b) and (c) correspond to $R = 15 \, \mu m$, $20 \, \mu m$ and $25 \, \mu m$ radii of curvature, respectively. The results corresponding to the A-type geometry are shown in red, those of the B-type are plotted in blue, and green results correspond to the C-type geometry. Solid lines are obtained fitting the responses to spectral shapes of Eqs. (2) and (3).

Curving a single waveguide with a finite radius $R$, besides of causing a change in the effective index and making it complex, produces a shift of the modal field intensity distribution mainly along the radial direction [13].
Figure 5: Measured through and drop responses of the add-drop resonators at a resonance placed at the central region of the C band. (a), (b) and (c) correspond to $R = 15 \, \mu m$, $20 \, \mu m$ and $25 \, \mu m$ radii of curvature, respectively. The results corresponding to the A-type geometry are shown in red, those of the B-type are plotted in blue, and green results correspond to the C-type geometry. Solid lines are obtained fitting the responses to spectral shapes of Eqs. (2) and (3).

The modification of the modal field and its impedance at the curved sections creates a discontinuity at the straight-bent interfaces that generates localized radiation beamed along the direction of the incoming optical field [10]. This
Figure 6: Measured through and drop responses of the add-drop resonators at a resonance placed at the short wavelength end of the the C band. (a), (b) and (c) correspond to $R = 15 \, \mu m$, $20 \, \mu m$ and $25 \, \mu m$ radii of curvature, respectively. The results corresponding to the A-type geometry are shown in red, those of the B-type are plotted in blue, and green results correspond to the C-type geometry. Solid lines are obtained fitting the responses to spectral shapes of Eqs. (2) and (3)

radiation can be reduced by shifting the relative central positions of the straight and bent waveguides at their junction so as to maximize the mode overlap between the mode field distribution in the two sections. This is the
so-called lateral shift technique \[12\] and its use is illustrated in Fig. 1.

The transmission of the input optical intensity to the through and drop ports (\(T_t\) and \(T_d\), respectively) in Fig. 1 is given by \[1\]

\[
T_t = r^2 \frac{a^2 - 2a \cos \phi + 1}{1 - 2r^2 a \cos \phi + (r^2 a)^2}, \tag{2}
\]

\[
T_d = \frac{(1 - r^2)^2 a}{1 - 2r^2 a \cos \phi + (r^2 a)^2}, \tag{3}
\]

where \(\phi = n_g 2\pi L / \lambda\) and \(a\) is the total attenuation factor of the optical field in one round-trip along the cavity. The group index at wavelength \(\lambda\) is given by

\[
N_g = N_{\text{eff}} - \lambda \frac{dn_{\text{eff}}}{d\lambda}, \tag{4}
\]

with \(N_{\text{eff}}\) the effective modal index.

The total Q factor is given \[1\] by the expression

\[
Q = \frac{\pi n_g L r \sqrt{a}}{\lambda_{\text{res}} (1 - r^2 a)}, \tag{5}
\]

whereas the intrinsic Q-factor, corresponds to the case where the resonator is decoupled from the input and output access waveguides \(r \to 1\) and is directly related with the round-trip loss \(a\) as

\[
Q_I = \frac{\pi n_g L \sqrt{a}}{\lambda_{\text{res}} (1 - a)}, \tag{6}
\]

where \(\lambda_{\text{res}}\) is the resonance wavelength.

### 3 Design

Our design strategy aims to the minimization of the total round-trip loss by optimizing both the continuous radiation quenching asymmetric coupler and the lateral offsets for the localized radiation at discontinuities.

In the calculations, the refractive index of silicon dioxide \[19\] has been taken as \(n_{\text{SiO}_2} = 1.4440\) at \(\lambda = 1550\) nm and that of silicon nitride \[20\] \(n_{\text{Si}_{3}\text{N}_4} = 1.9963\). The width of the main waveguide is taken as \(w = 1\) \(\mu\)m and the height of all the silicon nitride sections \(h = 300\) nm.

The introduction of an exterior, radiation quenching, curved section in Fig. 1B produces a splitting of the input mode in two (even and odd) modes, with the odd mode predominantly propagating in the main waveguide \[13\].
The modal losses for the lower sheet, as obtained with full 3D vector calculations using the \texttt{wgsm3d} software package \cite{15,14} expressed as \( \log_{10}(n_i) \), where \( n_i \) is the imaginary part of the complex modal effective index are shown in Fig. 2 for \( R = 15 \ \mu m \), \( R = 20 \ \mu m \) and \( R = 25 \ \mu m \).

Fig. 2 displays, for the three values of the bend radius considered, a main broad parameter region adequate for radiation quenching at small values of both the waveguide separation \( s \) and width of the exterior coupled waveguide \( w_e \). The fact that this favorable design zone of the two-dimensional parameter space is broad, with smooth variations of the optimization target, contributes to the broadband character of the designs and their resilience to fabrication tolerances. As \( R \) increases, the main valley of the curves in Fig. 2 shifts to larger values of \( s \) and \( w_e \). In our design we have used values of \( s = 1.3 \ \mu m \), \( s = 1.7 \ \mu m \) and \( s = 1.9 \ \mu m \) for \( R = 15 \ \mu m \), \( R = 20 \ \mu m \) and \( R = 25 \ \mu m \), respectively. The values of the exterior waveguide width have been set to \( w_e = 600 \ \text{nm} \), \( w_e = 600 \ \text{nm} \) and \( w_e = 700 \ \text{nm} \) for \( R = 15 \ \mu m \), \( R = 20 \ \mu m \) and \( R = 25 \ \mu m \), respectively.

The design of the lateral shifts at the straight-bent discontinuities has been based on the maximization of the mode overlap of the guided modes in the two sections \cite{10,17,13}. The calculated optimal offset values are \( l_{off} = 110 \ \text{nm} \), \( 90 \ \text{nm} \), and \( 70 \ \text{nm} \) for \( R = 15 \ \mu m \), \( 20 \ \mu m \) and \( 25 \ \mu m \), respectively.

All the designs have targeted an operation wavelength of 1550 nm. The self-coupling coefficients of the evanescent couplers are affected by the introduction of lateral offsets at the straight-bent discontinuities when straight input and output waveguides are used \cite{10}. The modification of the value of \( r \) would affect the total Q factor and would hinder a visual appreciation from the device responses of the effect of the proposed geometry modifications on the intrinsic Q factor. Therefore, the coupling sections in our devices are kept far from the terminations of the straight arms of the racetrack in order to preserve the values of \( r \) in cases A, B, and C.

4 Results

The Silicon Nitride chip was fabricated at the Instituto de Microeletrónica de Barcelona, Centro Nacional de Microeletrónica (IMB-CNM), CSIC \cite{18} through a Multi Project Wafer approach offered by VLC Photonics. The designed devices have been fabricated in a 5 mm \( \times \) 5 mm silicon nitride integrated circuit. Figure 3 displays micrographs of two of the fabricated devices with \( R = 15 \ \mu m \) corresponding to geometries A and B.

The fabricated devices have been characterized in the C band. Figures
4, 5 and 6 display the measured through and drop responses of the devices (dotted lines) at resonances placed at three different locations within the C band: close the short wavelength end, in its central region, and near the long wavelength end. The coupling losses from the measurement apparatus to the PIC are also included in these plots. The measured responses exhibit a rippling that is due to the etalon effect due to reflections at the end facets of the integrated circuits. Solid lines display the fitting of the measured data to the through 2 and drop 3 responses obtained using Matlab’s linear programming solver fminsearch.

In all the cases, the improvement of the Q-factors from all the cases corresponding to the conventional (A, red) geometry to that including the radiation quenching sections (B, blue) and the lateral offsets (C, green) is evident from the plots. Since the design preserves the value of $r$, as discussed in Section 3, this improvement can be directly assigned to the reduction of the total round-trip loss $a$ and the associated enhancement of the internal Q of the resonators.

The results of the linear programming fits permit to determine $a$ and the calculation of the intrinsic Q enhancement factors, defined as the ratio of the intrinsic Q factor of the two compared geometries

$$EF_{IJ} = \frac{Q_J}{Q_I}$$

The results are shown in Table 1. The magnitudes of the enhancement factors obtained due to the introduction of radiation quenching sections are comparable, but larger in almost all the cases cases, to those due to the presence of lateral offsets.

5 Conclusion

Q-enhanced racetrack microresonators have been fabricated in the silicon nitride platform and their responses have been characterized. The measurements performed confirm a significant reduction of the radiation losses in these structures, as predicted by previous theoretical studies. The microresonator geometries experimentally demonstrated permit reduced sized implementations when designed for the same operation conditions as their conventional counterparts and, therefore, they contribute to an increment of the integration scale in this platform. Furthermore, in the silicon nitride platform, restriction on the radii of curvature also apply to all the curved optical connections in the layout of any PIC in order to limit the effects of radiation loss. The Q-enhanced design strategy devised for micro-resonators can be
used in any curved waveguide section used to carry the optical signals in the circuit and it would allow for a reduction of the permitted radii of curvature, also contributing to the increase of the integration scale in this platform. Besides the radiation quenching properties of the geometry modifications employed in the Q-enhanced geometries, they also hold strong polarization dependent properties that can be exploited in the design of polarization control devices [17].

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