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View online: http://dx.doi.org/10.1063/1.4878337
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High-Q contacted ring microcavities with scatterer-avoiding “wiggler” Bloch wave supermode fields

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(Received 18 February 2014; accepted 5 May 2014; published online 19 May 2014)

High-Q ring resonators with contacts to the waveguide core provide a versatile platform for various applications in chip-scale optomechanics, thermo-, and electro-optics. We propose and demonstrate azimuthally periodic contacted ring resonators based on multi-mode Bloch matching that support contacts on both the inner and outer radius edges with small degradation to the optical quality factor (Q). Radiative coupling between degenerate modes of adjacent radial spatial order leads to imaginary frequency (Q) splitting and a scatterer avoiding high-Q “wiggler” supermode field. We experimentally measure Qs up to 258,000 in devices fabricated in a silicon device layer on buried oxide undercladding and up to 139,000 in devices fully suspended in air using an undercut step. Wiggler supermodes are true modes of the microphotonic system that offer additional degrees of freedom in electrical, thermal, and mechanical design. © 2014 AIP Publishing LLC.

Microcavities with attachments have important applications in integrated photonics. Ridge waveguides extend a flange of the core into the cladding, permitting electrical contacts, and good optical confinement to enable electro-optics modulators.\textsuperscript{1} Suspended microcavities relying on pedestals\textsuperscript{2} or inner spokes\textsuperscript{3,4} for mechanical support have been used in optomechanics. Many of these approaches have limitations: ridge waveguides require a partial etch step, neither available, for example, in standard complementary metal-oxide semiconductor (CMOS) processes\textsuperscript{5,6} nor suitable for suspended structures. Pedestal and inner-spoke cavities either rely on disk-like whispering gallery modes and provide limited degrees of freedom for mechanical design or have external contacts\textsuperscript{1,7} at the expense of substantial degradation in Q factor due to scattering.

Recently, an approach has been proposed to design multimode linear waveguides and resonators with periodic attachments that support modes whose fields avoid those attachments so as to maintain low propagation loss.\textsuperscript{8,9} High-Q resonators based on linear, periodically contacted waveguides that support low-loss “wiggler modes” were recently demonstrated.\textsuperscript{5,10} However, these cavities are large and require non-adiabatic tapers for single-mode to wiggler-mode transitions which may limit their loss Q.

In this paper, we demonstrate azimuthally periodic contacted ring microcavities comprising a multimode microring waveguide with periodic attachments to the inner and/or outer walls (Fig. 1(a)). These cavities implement a circular symmetry version of the structural Bloch matching and complex Q-splitting concept previously demonstrated in a non-resonant linear waveguide geometry.\textsuperscript{5,8,10} As in the linear devices, the attachments act as perturbations that lead to a radiative coupling (as opposed to the usual reactive coupling between coupled structures) that splits the first and second fundamental radial eigenmodes (of different azimuthal order and initially degenerate) of the ring in imaginary frequency. This results in a “wiggler” supermode with a field whose spatial distribution avoids the scattering attachments that contact the core, preserving a high Q (Fig. 1(b)), and another one with high scattering loss at the contacts and thus low Q. In a mode coupling picture, the attachments add both a real and an imaginary frequency shift to each mode, through each mode’s self-coupling with the perturbation. The physics that results in the low-loss supermodes is a cross-coupling between the modes, mediated by the periodicity-matched perturbation, which provides imaginary frequency splitting and recovers most of the imaginary frequency shift (loss) introduced by the self-coupling term. This concept has many applications, allowing electrically and thermally contacted resonators with great freedom in contact geometry and reasonably high optical Q. Further releasing of the devices from the substrate enables thermal isolation and mechanical suspension, which may be useful for thermo-optic effects and thermal isolation design as well as tuning of mechanical properties and optomechanics (light-forces-based devices on chip). We experimentally demonstrate silicon-core ring microcavities that are silica cladded with \( N = 6 \) contacts to the core at the outer radius, and show a low-loss resonant supermode with a Q of 258,000, and an air-suspended, smaller-radius ring with \( N = 4 \) contacts and a measured Q of 139,000.

To construct a contacted ring resonator that supports a high-Q “wiggler” supermode, we start with a single ring that has resonant modes with first- and second-order radial fields. Interference between these two modes allows the resulting supermode to have a field intensity pattern that wiggles back and forth between the inner and outer walls along the ring (Fig. 1(b)), with a periodicity determined by the difference in azimuthal mode orders. If an array of contacts is then introduced to the ring, the resulting scattering loss at the contact points can be seen as a perturbation of imaginary permittivity.

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to the original structure, which couples and splits the two modes in imaginary (and real) eigenfrequency (or equivalently in loss Q). As in real splitting, the coupling is maximized when the phase matching condition is met, i.e., when the periodicity of the contact array equals the difference in azimuthal mode numbers of the first- and second-order radial modes. This loss avoidance behavior of the high-Q "wiggler" mode can be understood as the excitation of the right relative amplitudes of the first-order and second-order radial resonant modes of a ring to produce a null in the beat pattern (spatial envelope) of the total electric field at the contact points. Note, however, that the "wiggler" supermode is an eigenstate rather than a superposition of multiple modes in the perturbed system with contacts, and a standard single-mode waveguide coupler suffices to excite this mode.

For experimental demonstration, microcavities were designed in a 220 nm-thick silicon device layer of typical custom silicon-on-insulator (SOI) wafers for photonics. Figure 2(a) plots the azimuthal mode numbers of the first-order radial mode ($\gamma_1$, blue dashed lines), and the difference between azimuthal mode numbers ($\gamma_1 - \gamma_2$, red solid lines) of the first and second radial modes in an unperturbed ring cavity without contacts. At crossing points of the red and blue contours, $\gamma_1$ and $\gamma_2$ are integers and both radial modes are resonant at the design wavelength of 1550 nm. Bending loss further restricts the dimensions at which high-Q modes can be obtained. Requiring high-Q initial (uncoupled) modes limits the design space to the upper right part of Fig. 2(a), for example, beyond contours of constant bending loss Q of $10^5$ or $10^6$, given as examples in the figure. The orange marker shows an example design, with $\gamma_1 = 32$, $\gamma_2 = 26$, and the bend-loss Q of the second mode without attachments just above $10^6$.

An azimuthally periodic array of contacts is then introduced, with periodicity equal to the beat length between the two degenerate modes—the number of attachment periods is equal to the difference in azimuthal orders of the two modes ($N = \gamma_1 - \gamma_2 = 6$). These attachments force the resonator into radiative splitting along the imaginary axis on the complex frequency plane (Fig. 2(b), left). This is in contrast to direct reactive coupling of resonators, which leads to real frequency splitting (Fig. 2(b), right). Since quality factor is related to the imaginary part of the complex resonant frequency ($Q = \omega_0 R / (2 \omega I)$), the imaginary splitting leads to a high-Q supermode whose field distribution spatially avoids the scattering contacts (illustrated in Fig. 2(c), left), and a complementary low-Q supermode whose field distribution has strong overlap with the contacts (Fig. 2(c), right).

Figure 3(a) shows an optical micrograph of a fabricated device with $N = 6$ contacts attached to the outer wall of the resonator. An array of devices was designed around the optimum parameters to account for fabrication variations and to show that a particular combination of radius and width is
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While the port transmission, which means that the total Q is dominated by the cavity loss Q, not the external coupling. While the transmission is dominated by the cavity loss Q, not the external coupling. 

Note that the drop port is over 15 dB beneath the through port, which means that the total Q is dominated by the cavity loss Q, not the external coupling. Note that here four modes are near-degenerate prior to inclusion of the attaching structures. In this case, a lack of azimuthal invariance of the modes due to contra-directional coupling (note that here four modes are near-degenerate prior to inclusion of the attaching structures). In this case, a lack of azimuthal invariance of the structure contributes enhanced contra-directional coupling. In this case, a lack of azimuthal invariance of the structure contributes enhanced contra-directional coupling.

FIG. 3. (a) Microscope image of a fabricated ring resonator with 6 attachments. (b) Measured through- and drop-port spectral responses. Inset: resonance with a Q factor of 258 000. (c) High-Q resonances of 6 devices with linear width variation show an optimum design with maximum Q factor. (d) Zoomed out view of c showing wider spectra.

required for high-Q operation. The best-performing device was designed with a target outer radius of 3.89 μm, (multi-mode) ring cross-section of 990 × 220 nm, and contact width of 100 nm. For this device, Fig. 3(b) shows the highest measured Q factor of 258 000. The observed resonance doublet is a result of the typical splitting of high-Q traveling-wave modes due to contra-directional coupling (note that here four modes are near-degenerate prior to inclusion of the attaching structures). In this case, a lack of azimuthal invariance of the structure contributes enhanced contra-directional coupling. In this case, a lack of azimuthal invariance of the structure contributes enhanced contra-directional coupling. The drop port is over 15 dB beneath the through port transmission, which means that the total Q is dominated by the cavity loss Q, not the external coupling. While the highest observed Q was 258 k, many devices with a loss Q over 100 k were measured.

Evidence that the thin contacts visible in Fig. 3(a) are not inconsequential, i.e., that our design approach is necessary to obtain high Q, is provided in Fig. 3(c). The figure shows drop-port spectra of representative devices with a fixed waveguide-cavity coupling gap (250 nm) and radius (Rcorner = 3.4 μm), while the width is linearly varied (see Fig. 3(c)). The resonances red-shift with increased width due to increase in effective index. However, the transmission and the Q increase (line-width decreases) as one approaches the center device from either side. These both confirm that the highest loss Q is in the central device, as the waveguide coupling is broadband and does not contribute to variation in insertion loss from one resonance to the next. In addition, these spectra show very broad, low transmission resonances interspersed between the high Q ones (e.g., see broad resonances in Fig. 3(d)). These resonances represent the complementary, low-Q resonant supermodes that result from the imaginary frequency splitting.

A different device designed for air cladding on both sides of the silicon layer was fabricated on the same chip and further released in post processing (Fig. 4). Etch windows are created on a chromium mask and transferred to a 900 nm layer of positive resist (NR9-1000P) covering the chip. After development, buffered oxide etch (BOE) is used to selectively remove the oxide under the resonator region. To avoid sticking of the device to the bottom silicon due to surface tension in normal evaporative drying, after rinsing in deionized water, isopropyl alcohol (IPA) is used to replace the liquid covering the chip, which is then removed in a CO2 critical point dryer.

Figure 5(a) shows a scanning electron micrograph (SEM) image of a released structure and a zoomed in picture of the resonator. The device is a ring resonator with 4 contacts connected to an input and an output coupling waveguide, similar to the 6-contact device shown in Fig. 3(a). The small squares visible on the four corners are density fill patterns required in the SOI fabrication process for process uniformity. BOE etching was timed to remove the entire thickness (2 μm) of the silica under the device layer, and some fill shapes within the etch window were removed from the chip during the etching and drying, leaving pyramid shaped residuals at their original sites. A higher magnification SEM image on the right confirms that the air-suspended resonator is supported by its 4 contacts connecting it to the partially released waveguides. Direct mechanical connection to a waveguide can be a useful feature for suspended photonic structures, as built in stresses in the device layer can produce out of plane misalignment of adjacent waveguides and other structures without proper stress relief within the design. In this paper, we did not design scattering avoiding structures into the waveguide as well, only the resonator, since the waveguide sees only a single pass loss. However, straight wiggler mode taper arms could be incorporated in the bus waveguide, similar to those in racetrack
resonators,\textsuperscript{6,10} to minimize overall transmission loss of attached wiggler-mode cavities.

Figure \textsuperscript{5(b)} shows measured through- and drop-port spectral responses. Inset: resonance with a Q factor of 139 000.

The design may be enabling for applications in light-force actuated photonics on chip, e.g., for state trapping and self-adaptive photonics,\textsuperscript{14} very efficient thermal tuning by allowing mechanical suspension with potentially higher thermal impedance than, e.g., microdisks on a pedestal or even wheel resonators, as well as in other applications such as enabling the tighter mode confinement of an air-silicon interface within a microcavity.

This work was supported by National Science Foundation Grant No. ECCS-1128709. Fabrication was done at IMEC, Belgium, through the ePIXfab Multi-Project Wafer silicon photonics shuttle runs (IMEC10).