Air-suspended High-Q Ring Microcavities with Scatterer-Avoiding “Wiggler” Supermode Fields

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Abstract: We demonstrate air-suspended high-Q ring resonators based on multimode Bloch matching and resultant scatterer-avoiding “wiggler” supermode field. Device designs are fabricated in silicon-on-insulator and undercut to form air-suspended structures with measured Q’s up to 139,000.

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On-chip ring microcavities with contacts constitute a versatile platform with applications in optomechanical, optoelectronic and thermally tunable photonic devices. To minimize optical scattering loss from contacts, ridge waveguides [1], toroidal resonators with pedestals [2] and wheel resonators with inner spokes [3] have been used to access the core of the resonant cavities with minimal impact on the optical quality factor or radiation loss Q. We previously proposed a family of structures supporting optical fields that avoid the scattering contacts by forming a unique low-loss Bloch mode [4–6] and demonstrated a new microcavity geometry that relies on this concept to permit contacts to the outer and inner radius of a ring [6]. These “wiggler-mode” resonators provide a new cavity geometry that allows additional degrees of freedom in device design, including mechanical geometry, and are realizable in a single lithographic step in standard CMOS processes.

In this paper, we report the experimental demonstration of “wiggler” resonators designed to be air suspended, enabling light-force actuation [7], efficient thermal tuning [8], and other applications. The devices were fabricated in the 220 nm-thick silicon device layer in silicon-on-insulator (SOI) platform [9], and further post processed to have the resonator region fully suspended in air. “Wiggler” resonators are azimuthally periodic microcavities comprising a multimode microring waveguide with periodic contacts (Fig. 1a) [6]. The contacts act as perturbations to the microring, which lead to radiative coupling that splits the first and second fundamental transverse eigenmodes of the ring in imaginary frequency. This results in a supermode with a field whose spatial distribution avoids the scattering contacts to preserve a high optical Q (Fig. 1b). Demonstration of high Q in suspended “wiggler” resonators is an important step in establishing the feasibility of this concept for application in more complex photonic circuits that will rely on mechanical degrees of freedom, or other properties of air-suspended structures such as thermal isolation. Here, we experimentally demonstrate air-suspended silicon “wiggler” microcavities with N = 4 contacts to the core at the outer radius, and show a low-loss resonant supermode with a Q above 139,000.

To design a “wiggler” resonator with N = 4 contacts, the outer radius and waveguide width of the ring are chosen such that at particular longitudinal orders differing by γ1−γ2 = 4, the resonant frequencies of modes belonging re-

(a)   (b)  

Fig. 1: Wiggler microcavities: (a) Illustration of wiggler microcavity with azimuthally periodic contacts. (b) Two degenerate resonances of an unperturbed ring (1st-order transverse mode with azimuthal mode number γ1 = 8, and 2nd-order transverse mode with γ2 = 4). A superposition of these modes, which forms a low-loss supermode under the scattering perturbation, has a vanishing field intensity at the contact points.
Fig. 2: Design of air-suspended wiggler microcavities: (a) Azimuthal mode number ($\gamma$) of 1$^{st}$ order transverse mode of an unperturbed ring at 1550 nm (blue), difference between azimuthal mode numbers of 1$^{st}$ and 2$^{nd}$ order transverse modes ($\gamma_1 - \gamma_2$, red), and bending loss Q of the 2$^{nd}$ transverse mode (green) versus ring width and outer radius. Orange marker labels the actual design implemented (air-suspended silicon ring with 4 contacts, outer radius = 2.04 $\mu$m, ring width = 0.958 $\mu$m). (b) 3D eigenmode simulation of the “wiggler” supermode field in 1/8 of a microcavity using symmetry boundary conditions (in HFSS eigensolver with PML absorbing boundaries).

Respectively to two transverse eigenmode families (1$^{st}$ and 2$^{nd}$-order) in an unperturbed multimode ring are the same, at the design wavelength of 1550 nm. Figure 2a plots the design map for a 220 nm silicon layer with air on top and bottom from mode solver simulation of rings without contacts. In Fig. 2a, the design requirement corresponds to intersection points of the $\gamma_1 - \gamma_2 = 4$ line and any blue line. 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 unshaded part of Fig. 2a. The orange marker shows the device design used in this paper, with $\gamma_1 = 18$, $\gamma_2 = 14$, and the bend-loss Q of the second mode without attachments just above $10^6$. The outer radius is 2.04 $\mu$m and ring width is 0.958 $\mu$m, with additional pre-compensation for the resonance frequency shifts expected from the index perturbation introduced by the attachments, extrapolated from 2D simulations. Variations were also introduced to account for fabrication error. Figure 2b shows 3D simulation of 1/8 of the “wiggler” resonator with the supermode field intensity profile bending back and forth away from the inner and outer contact points, showing the “wiggler mode” is a true bona-fide eigenmode of this microcavity, in a full 3D vector-field problem.

Figure 3a shows the process flow for suspending the fabricated resonators. A copper mask is created with etch windows in dark field. A 900 nm-thick layer of positive resist (NR9-1000P) is spun onto the chip at 4000rpm for 40s. The coated chip is then aligned to the mask and exposed for 15s. After development, the chip is submerged in buffered HF (BOE) for 20min to selectively remove the oxide (2 $\mu$m thick) under the resonator region. To avoid sticking of the suspended device to the bottom silicon wafer substrate due to surface tension in normal evaporative drying, after rinsing in DI water, IPA is used to replace the liquid covering the chip, and is eventually removed in CO$_2$ critical point dryer.

Suspended and critical point dried devices are inspected under an SEM (Fig. 3b), and the images show that the oxide under the resonator and part of the coupling waveguides is removed. The small squares visible on the four corners are density fill pattern required in the SOI fabrication process for process uniformity [9]. 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 the four 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 [10].

Figure 3c shows measured through- and drop-port spectral responses from a suspended “wiggler” resonator with a quality factor of 139,000, indicating low loss. In comparison to devices that are not suspended [6], these structures also show significantly stronger thermal nonlinearity under higher input power.

We believe that the demonstrated resonators may enable important new degrees of freedom in design of photonic and nanomechanical structures for light-force actuated photonic structures, e.g. for state trapping and self-adaptive photonics [7], very efficient thermal tuning by allowing mechanical suspension with potentially higher thermal impedance.
Fig. 3: Experimental demonstration: (a) Process flow for suspending the resonators. A positive resist is spun onto the substrate and patterned with a copper mask to serve as an etch window; oxide under the resonator is selectively etched with a buffered HF solution (BOE); liquid covering the chip is replaced with IPA which is then removed in a CO$_2$ critical point dryer. (b) Scanning electron microscope (SEM) images of an air-suspended ring resonator with 4 contacts attached to coupling waveguides (left) and a zoomed in image of the resonator region (right). (c) Measured through- and drop-port spectral responses. Inset: resonance with a Q factor of 139,000.

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.

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References