Double-Notch-Shaped Microdisk Resonator-Based Devices in Silicon-on-Insulator

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Abstract: We demonstrate double-notch-shaped microdisk resonator-based filters with waveguide butt-coupling in silicon-on-insulator. Our filter demonstrates whispering-gallery-like modes with Q exceeding 10^4 . We also propose and fabricate electro-optic modulators using this structure integrated with a metal-oxide-semiconductor capacitor.

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Recently, spiral-shaped microdisk resonators with a single notch for non-evanescent coupling has been investigated by some of us (XL and AWP) for waveguide-coupled channel filter applications, with the spiral notch seamlessly jointed with a singlemode waveguide [1]. Such non-evanescent coupling via the notch has also been demonstrated to be high- Q resonances preserving [2]. However, the single-notch design still imposes an additional evanescently side-coupled waveguide for I/O devices. Here, we propose and experimentally demonstrate a waveguide-coupled double-notch-shaped microdisk resonator, which offers the key merit of non-evanescent input- and output-coupling for I/O devices. We propose passive device application of this structure as channel filters, and active device application as electro-optic modulators using a selectively integrated ring-shaped metal-oxide-semiconductor (MOS) capacitor on a silicon-on-insulator (SOI) substrate.

Figure 1(a) shows the schematic of the double-notch-shaped microdisk-resonator based channel filter. The microdisk shape comprises two non-identical hemi-circles with radii of R_1 and R_2 . The mismatches between the two hemi-circles on both sides of the diameter give two notches with widths of w_1 and w_2 . Each notch is seamlessly jointed to a waveguide of the same width. Thus, the light can be directly in/out-coupled via these notch-waveguides without relying on evanescent field. The input-coupled lightwave from each notch-waveguide can be partially out-coupled via the other one. The round-trip cavity light tends to bypass the input-coupled notch junction, and can be wavefront-matched with the input-coupled lightwave. Thus, it is conceivable that such structure can act as a channel rejection filter.

Fig. 1 (a) Schematic of the double-notch-shaped microdisk-based filter. The blue arrows represent the cavity light circulation. The dashed line represents the matched wavefront. (b) FDTD-simulated TE-polarized throughput transmission spectrum. Inset: Simulated steady-state mode-field pattern of resonance A. (c) Scanning electron micrograph of our fabricated double-notch-shaped microdisk-based filter in SOI, with selectively integrated poly-silicon ring/gate oxide structure along the microdisk rim. Inset: zoom-in view of the notch junction. (d) Measured TE-polarized throughput transmission spectrum.

We numerically simulate the double-notch-shaped microdisk resonators using finite-difference time-domain (FDTD) technique. We adopt two hemi-circles with radii of $R_1 = 5 \mu\text{m}$ and $R_2 = 4.6 \mu\text{m}$, giving

identical notch size of $w_1 = w_2 = 0.4 \mu\text{m}$. We use an effective refractive index contrast of 3.14-to-1.74 in order to represent the 0.34- μm -thick microdisk/waveguide core and the 0.05- μm -thick slab region in SOI with low-temperature oxide (LTO) upper cladding. Figure 1(b) shows the simulated TE-polarized (E-field in plane) throughput spectrum. We identify a free-spectral range (FSR) of $\sim 24.2 \text{ nm}$, which is consistent with the microdisk circumference. The inset shows the simulated steady-state mode-field pattern of mode A. We observe a whispering-gallery (WG)-like resonance, with lightwave directly in/out-coupled via the two notch-waveguides.

We fabricate the filter in SOI. Figure 1(c) shows the scanning electron micrograph of our fabricated device with $R_1 = 50 \mu\text{m}$, $R_2 = 49 \mu\text{m}$, and $w_1 = w_2 = 1.0 \mu\text{m}$. The waveguide and the microdisk are 0.34- μm high with an etched depth of $\sim 0.29 \mu\text{m}$. We selectively integrate a ring-shaped MOS capacitor structure in the microdisk rim region as a test structure for designing electro-optic active devices (see below). The MOS ring has a 15-nm-thick gate-oxide layer sandwiched between the microdisk top surface and a 0.2- μm -thick poly-silicon (poly-Si) ring. The inset shows the zoom-in view of the notch junction.

Figure 1(d) shows the measured TE-polarized throughput transmission spectrum of this device. We discern six cavity modes in such large-sized waveguide-coupled microcavity. We measure a FSR of $\sim 2.1 \text{ nm}$, which is consistent with the microdisk circumference. This suggests that the resonance is WG-like mode. The measured highest Q is $\sim 30,000$, meaning that such double-notch-shaped microdisks preserve high-Q modes. The MOS capacitor ring structure does not appear to suppress the resonance modes.

For active device applications, we propose a double-notch-shaped microdisk resonator-based electro-optic modulator with selectively integrated ring-shaped vertical MOS capacitor [3,4]. The principle is that the WG-like mode field in the microdisk rim spatially overlaps with the accumulated free carriers in close proximity to the gate-oxide interfaces, and thus can be wavelength modulated at a high speed with low power. Our previous semiconductor device simulations using MEDICI and waveguide-mode simulations using beam-propagation method suggested that the effective refractive index change of $\sim 10^{-3}$ is possible, by assuming the accumulated carriers are distributed over a thin layer of $\sim 10 \text{ nm}$ in the proximity of the gate-oxide interfaces [4]. This is also consistent with the literature [3].

Fig. 2 (a) Optical micrograph of our initially fabricated microdisk modulator integrated with a ring-shaped MOS capacitor. (b) Optical microscope zoom-in view of the MOS-integrated double-notch-shaped microdisk. (c) Schematic cross section of the microdisk rim with an integrated MOS capacitor. H : etched depth $\sim 0.29 \mu\text{m}$, h : slab height $\sim 0.05 \mu\text{m}$.

We conduct the initial fabrication of this modulator in SOI, using standard silicon microelectronics processes, including i-line photolithography, CF_4 -based reactive ion plasma etching, low-pressure chemical vapor poly-silicon deposition, ion implantation, aluminum sputtering and etching. Figure 2(a) shows the optical micrograph of our fabricated device in SOI. Figure 2(b) shows the zoom-in view optical micrograph of the MOS-integrated microdisk. The microdisk has the same size and notch widths as the filter (Fig. 1(c)). Figure 2(c) shows the cross-sectional view of the vertical structure. We are currently characterizing the modulator.

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