Silicon-on-insulator tunable waveguide-coupled microdisk resonators with selectively integrated p-i-n diodes

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Abstract: We report a design and analysis of compact silicon-on-insulator tunable waveguide-coupled microdisk resonators with selectively integrated p-i-n diodes. Our simulations suggest that singlemode resonances can be coupled and blueshifted by free-carrier plasma dispersion effect.

OCIS codes: (230.5750) Resonators; (230.2090) Electro-optical devices

Silicon-based active devices such as tunable filters, switches and modulators using free-carrier plasma dispersion effect have long been attracting considerable research interest [1]. However, typical refractive index change Δn demonstrated is only in the order of 10^{-3}, which imposes relatively long mm- to cm-sized phase-shifters in conventional Mach-Zehnder interferometer designs [1,2]. In order to attain compact active silicon devices that are sensitive to small Δn, Barrios *et al.* recently proposed and demonstrated compact silicon-on-insulator (SOI) tunable Fabry-Perot microresonators using Bragg mirrors with laterally integrated p-i-n diodes [3].

In this summary, we propose and analyze compact SOI tunable laterally waveguide-coupled microdisk resonators with selectively integrated lateral p-i-n diodes. We also report initial experimental results of SOI passive laterally waveguide-coupled microdisk resonators as a necessary step towards active SOI microdisk devices.

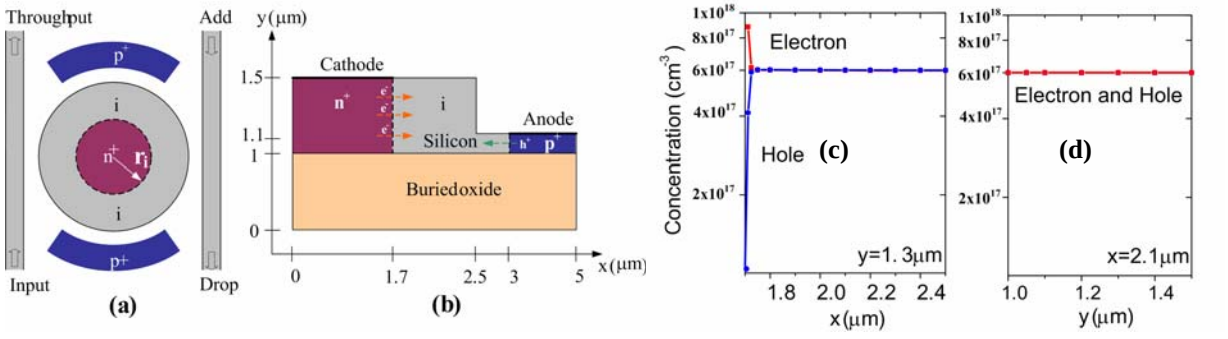

Fig.1. (a) Schematic of a SOI waveguide-coupled microdisk resonator with selectively integrated lateral p-i-n diodes as a tunable channel add-drop filter. (b) Schematic cross-section of the lateral p-i-n diode (under forward bias). (c) Horizontal distributions of free-carriers concentration along y=1.3 μm in the intrinsic region. (d) Vertical distributions of free-carriers concentration along x=2.1 μm in the intrinsic region.

Figure 1 (a) shows the schematic of an active microdisk resonator side-coupled with submicrometer single-mode input and output-coupled waveguides. We use lateral p-i-n diodes with n^+-doped region in the microdisk central region and p^+-doped region outside the microdisk rim. Upon forward bias, free-carriers are

selectively injected into the arc intrinsic region with lateral p-i-n diodes. The arc region refractive index and absorption can then be selectively tuned by means of free-carrier plasma dispersion effect. Doping can be made by implantation in order to precisely control the lateral dopant profiles. Figure 1 (b) shows the schematic cross-sectional view of our lateral p-i-n diode.

We used semiconductor device simulator MEDICI to simulate the free-carriers concentration profiles. We assumed a uniform dopant concentration of 10^{20} cm^{-3} for the n^+ region and of 10^{19} cm^{-3} for the p^+ region. Figures 1 (c) and 1 (d) show the calculated electron and hole-carrier distributions by applying a forward bias voltage of 0.91 V at y = 1.3 μm and x = 2.1 μm in the intrinsic region. We observed a flat distribution of about $6x10^{17}$ cm^{-3} for both carriers. Using the free-carrier dispersion at a wavelength of 1550 nm [4], we calculated the refractive index change $\Delta n = -0.002$ and the associated free-carrier absorption coefficient change $\Delta\alpha = 8.7$ cm^{-1}at the intrinsic region, and a substantial $\Delta\alpha = 850$ cm^{-1} at the central n^+ region. Hence, by selectively integrating the lateral p-i-n diodes, we achieve two objectives – (i) preferentially inject carriers to the intrinsic rim region to phase-shift the low-order whispering-gallery modes (WGMs), and (ii) suppress the undesirable high-order WGMs by excessive free-carrier absorption in the microdisk central region.

We used two-dimensional finite-difference time-domain (FDTD) simulations to demonstrate the suppression of high-order WGMs by tuning the size of the heavily doped central region. Here we fix the n^+-concentration at 10^{20} cm^{-3}. We simulated a 5-μm diameter microdisk resonator. Figures 2 (a) and 2 (b) show the FDTD simulated transmission spectra with the n^+ disk radius r of 1.2 μm and 1.7 μm. With an increase in the central n^+ doped area, the low-order mode A is only slightly shifted (with essentially fixed Q and coupling efficiency), whereas the high-order mode B is partially suppressed. Figure 2 (c) shows the simulated steady-state mode-field patterns of modes A' and B' with the r = 1.7 μm n^+ doped region.

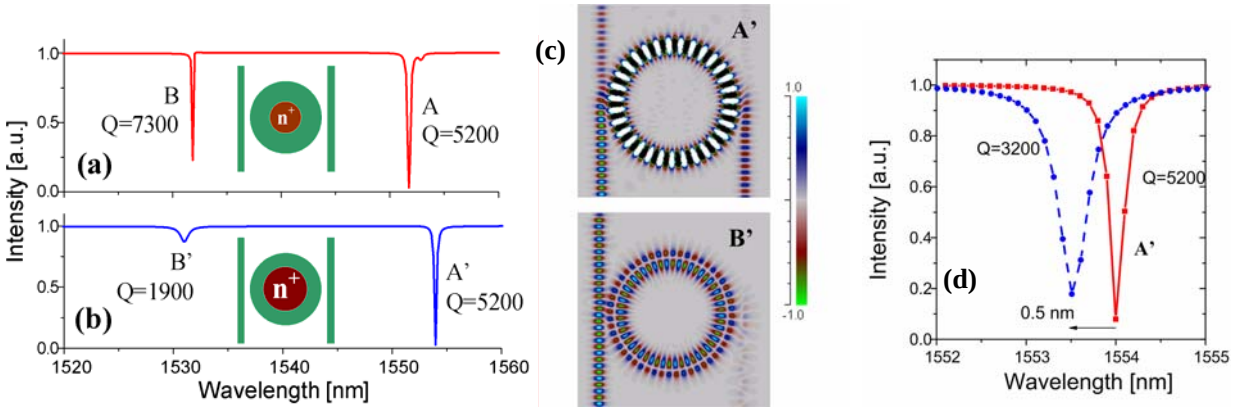

Fig.2. FDTD-simulated transmission spectra at throughput port for 5-μm-diameter microdisk resonators (TM polarized). (a) n^+ doped disk radius r = 1.2 μm, and (b) r = 1.7 μm. We adopted the waveguide refractive index n=3.45, and the background refractive index of 1.45. (c) Simulated steady-state mode-field patterns of the low-order mode A' and of the partially suppressed high-order mode B'. (d) Simulated mode A' transmission when there is no bias (solid line) and the blueshifted resonance transmission upon a forward biasing of 0.91 V (dashed line).

Figure 2 (d) shows the FDTD-simulated mode A' resonance blueshift of about 0.5 nm upon a forward bias of 0.91 V by imposing a $\Delta n = -0.002$ and $\Delta\alpha=8.7$ cm^{-1} along the arc region with carrier injection. Here we assumed the total active arc length is one-half of the total microdisk circumference (Fig.1(a)). When there is no bias (solid line), the resonance has a Q = 5,200 and a coupling efficiency of about 92 %. Upon forward bias (dashed line), the blueshifted resonance has a reduced Q =3,200 and a reduced coupling efficiency of about 85 %.

As a necessary step towards active SOI microdisk devices, we demonstrate for the first time to our knowledge SOI passive laterally waveguide-coupled microdisk resonators. We employed standard silicon microfabrication processes. Figure 3 (a) shows the scanning-electron micrograph of our initially fabricated waveguide-coupled 50-μm-diameter passive microdisk resonator on 0.5-μm SOI substrates. Inset shows the cross-sectional view of the side-coupled submicrometer singlemode waveguide with a waveguide height of about 0.35 μm and a width of about 0.35 μm. Figure 3 (b) shows the measured multimode throughput transmission spectrum with TE polarization. Figure 3 (c) shows a zoom-in view of a high-Q mode (Q ≈ 32,000) with exceeding 16 dB coupling efficiency. This high-Q value is an order of magnitude higher than that recently reported in SOI waveguide-coupled microring resonator [5].

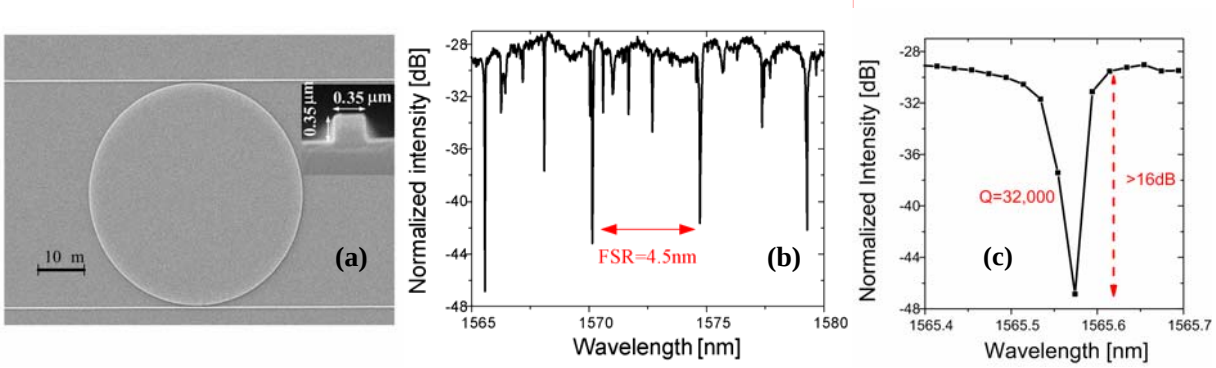

Fig.3. (a) Scanning-electron micrograph of SOI passive waveguide-coupled microdisk resonator on 0.5 μm SOI. Inset shows the cross-sectional view of the submicrometer singlemode waveguide. (b) Measured multimode throughput transmission spectrum with TE polarization. The free-spectral range (FSR) of 4.5 nm is consistent with the microdisk circumference. (c) Zoom-in view shows the high-Q mode with Q ≈ 32,000 and a coupling efficiency > 16 dB.

In summary, we report a design and analysis of injection-type active microdisk resonator devices using selectively integrated lateral p-i-n diodes. We took advantage of the large optical absorption loss in the heavily doped microdisk central region in order to suppress undesirable high-order whispering-gallery modes. While the lateral p-i-n diodes selectively inject carriers to phase-shift the low-order whispering-gallery modes along the microdisk rim. Our simulations suggested a resonance wavelength blueshift of about 0.5 nm under a forward bias of only 0.91 V. We also experimentally demonstrated for the first time to our knowledge SOI passive waveguide-coupled microdisk resonators with a high Q of about 32,000 and a high coupling efficiency exceeding 16 dB. Design optimization and fabrication of the proposed SOI active microdisk devices using standard silicon microfabrication processes are in progress.

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