Waveguide-coupled Square Micropillar Resonator-based Devices: Channel Filters and Electro-optic Switches with Embedded p-i-n Diodes

Chao Li, Linjie Zhou, and Andrew W. Poon
Department of Electrical and Electronic Engineering, The Hong Kong University of Science and Technology
Clear Water Bay, Hong Kong SAR, China
Tel: (852)-2358-7905, fax: (852)-2358-1485, email: eeawpoon@ust.hk

ABSTRACT
We report our numerical calculations and initial experiments on waveguide-coupled square micropillar resonator-based devices. Our calculations using two-dimensional finite-difference time-domain simulations and Fourier analysis show that waveguide coupling to a micropillar with a long flat coupling sidewall enables desirable directional wavevectors in the micropillar, and thus potentially gives rise to preferentially coupled modes in waveguide-coupled large-size square micropillar resonators. Our initial experiments on silicon-based waveguide-coupled large-size square micropillar resonator-based filters, with tailored cavity corners, reveal only 2 – 3 modes. We also experimentally demonstrate injection-type square micropillar resonator-based silicon electro-optic switches using laterally integrated p-i-n diodes across the entire square microcavity. By applying a 4 V forward-bias driving voltage, we obtain a resonance wavelength blueshift of ~ 0.54 nm. We measure the device bandwidth to be about 2 MHz, primarily limited by a wide intrinsic region.

Keywords: waveguide-coupled, square micropillar resonator, electro-optic device, p-i-n diode.

1. INTRODUCTION
Silicon-based waveguide-coupled planar optical microresonators that exhibit sharp resonances and micrometer in size have attracted substantial recent research interest for realizing photonic integrated circuits on microchips. Most of these works employ conventional microring [1] or circular microdisk [2] resonators as wavelength-selective passive or tunable filters. Recently, silicon electro-optic modulators using microring resonators with embedded p-i-n diodes have also been demonstrated with GHz-speed [3]. However, high-index-contrast circular microring and microdisk resonators have undesirable highly curved sidewalls that impose a limited interaction length for lateral coupling with straight waveguides, typically through a technological-challenging ~ 0.2 µm gap separation. Besides, waveguide-coupled circular microdisk resonators tend to be highly multimode. Although racetrack ring microresonators has long been proposed as an alternative microring resonator design to lengthening the lateral coupling length, the racetrack straight waveguide-to-curved waveguide junctions and the racetrack ring inner sidewalls still impose substantial cavity losses.

Previously, we proposed and examined waveguide-coupled polygonal micropillar resonators [4-6], in the shape of square, hexagon, and octagon, as alternative lateral waveguide-coupled microresonator-based filter designs. Our initial proposal pointed out that the key merit of the polygonal micropillar resonators is that the flat micropillar resonator sidewalls enable long interaction lengths with laterally coupled straight waveguides. We, as well as other workers, also showed that properly deformed polygonal micropillar resonators, such as cutting [4, 7] or rounding [7-9] the cavity corners, can enhance the cavity quality factors [4, 7-9], reduce the number of waveguide-coupled modes [4], and enhance the resonance extinction ratio [4, 9].

Here we report our latest analysis on waveguide-coupled square micropillar resonators, and initial experimental demonstrations on waveguide-coupled large-size square micropillar resonator-based filters and electro-optic switches on silicon-on-insulator (SOI) substrates. Our numerical simulations and Fourier analysis suggest that waveguide lateral coupling to a long flat sidewall enables directional k-vectors in the coupled microstructure. By tailoring the square micropillar resonator corners, we demonstrate only 2 – 3 modes in waveguide-coupled large-size square micropillar resonators. We also study p-i-n diodes integrated silicon square micropillar resonators.

2. ANALYSIS OF WAVEGUIDE-COUPLED MICROPILLARS WITH A FLAT SIDEWALL
We employ two-dimensional finite-difference time-domain (FDTD) method to simulate waveguide coupling to planar microstructures with a flat sidewall, and Fourier analyze the simulated field patterns in k-space. We assume a semi-infinite microstructure with no other boundaries. We choose refractive index $n = 3.5$ in order to represent a silicon waveguiding layer and $n = 1.44$ to represent a silica side cladding. We adopt a waveguide...
width $w = 0.27 \mu m (\phi = 45^\circ)$ in order to preferentially couple to 4-bounce orbit modes of a square microresonator [4]. We assume a relatively wide air-gap separation $g = 0.3 \mu m$ between the waveguide sidewall and the planar microstructure sidewall. Such gap separation is more practical for photolithography.

Figure 1a shows the simulated H-field patterns (TE-polarization; E-field in plane) of a waveguide-coupled (square) planar microstructure with a flat coupling sidewall of 10 $\mu m$ length. Only the coupled field in the planar microstructures is shown. The coupled traveling wave field distribution displays relatively flat wavefronts, and thus suggests directional $k$-vectors in the direction according to the waveguide mode. In contrast, Fig. 1b shows the simulated H-field patterns of a waveguide-coupled (circular) planar microstructure with a curved coupling sidewall of 5 $\mu m$ radius. The coupled traveling wave field distribution with spherical wavefronts suggests a relatively large angular distribution (with focusing and diffraction).

Figure 1. Simulated TE-polarized steady-state H-field pattern for the silicon waveguide-coupled planar microstructures with (a) flat sidewall of length $a = 10 \mu m$, and (b) curved sidewall (radius of 5 $\mu m$). The dashed box indicates the area of size $a$ under Fourier analysis. $k_{wg}$: waveguide mode $k$-vector, $\phi$: $k_{wg}$ angle relative to the waveguide sidewall normal, $k^\prime$: coupled $k$-vector, $\theta$: $k^\prime$ angle relative to the sidewall normal.

Figure 2a shows the Fourier analysis of the simulated field pattern that is inside the dashed-line square box of size $a$ as shown in Fig. 1a. We define the $k_x$ and $k_y$ components in units of $\pi/a$, and $k_x^2 + k_y^2 = (nk)^2$. The $k$-space distribution is localized near the central angle $\theta$ with a full-wave half-maximum angular range of $\Delta \theta$. The ratio of $\theta/\Delta \theta$ provides a measure on the coupled wavevectors directionality. Figs. 2b and 2c show the calculated $\theta$ and $\theta/\Delta \theta$ values of waveguide-coupled planar microstructures with various sidewall lengths using three different waveguide widths that favour coupling to 4-bounce modes in a square microresonator. We see that $\theta$ rises with sidewall length and saturates at the waveguide mode angle $\phi$ as sidewall length exceeds about 5 $\mu m$. Whereas $\theta/\Delta \theta$ linearly increases with sidewall length up to at least 20 $\mu m$ sidewall length. Thus, the coupled $k$-vectors become more directional with a long flat coupling sidewall.

Figure 2. (a) Fourier analysis of the simulated steady-state field patterns in Fig. 1(a). (b), (c) Simulated $\theta$'s and $\Delta \theta/\theta$'s of waveguide-coupled planar microstructures with various sidewall lengths of different waveguide width.

3. SILICON WAVEGUIDE-COUPLED SQUARE MICROPILLAR RESONATOR-BASED FILTERS

Here we report our initial experimental demonstrations of waveguide-coupled square micropillar resonator-based filters on a SOI substrate with a 0.2-$\mu m$ device layer and a 2-$\mu m$ buried-oxide layer. The fabrication employs standard silicon microelectronics fabrication processes. We prepare the devices using photolithography (i-line) and RIE dry-etching. The etched depth is $\sim 0.15 \mu m$. The devices are air-clad.

Fig. 3a shows the top-view scanning-electron micrograph of a waveguide-coupled 30-$\mu m$-size square micropillar resonator-based filter. The square microcavity corners are intentionally cut at 45$^\circ$ by 3 $\mu m$ [4], giving a sidewall interaction length of 24 $\mu m$. The designed waveguide width is 0.3 $\mu m$ (giving an $\phi \sim 46^\circ$) and the designed gap separation between the waveguide and the resonator is 0.35 $\mu m$. Fig. 3b shows the measured
TE-polarized throughput-port spectrum of a waveguide-coupled 30-µm-size square micropillar resonator-based filter. We observe only about 3 distinct modes with the maximum Q ~ 3,800. The measured free spectral range (FSR) is ~ 7.7 nm, which is consistent with a 4-bounce orbit round-trip length (of θ ~ φ ~ 46°). We attribute the relatively few coupled modes to the directional wavevectors coupled along the long flat sidewall. According to the k-space analysis (Fig. 2), we expect a directionality of θ/Δθ ~ 22.

4. SILICON ELECTRO-OPTIC SWITCHES USING SQUARE MICROPILLAR RESONATORS

We also report our initial experimental work on silicon electro-optic switches using square micropillar resonators with laterally integrated p-i-n diodes. It has been known that silicon microresonator resonance wavelengths can be blueshifted upon current injection due to the free-carrier plasma dispersion effect [3, 10].

Figure 4a shows the top-view scanning-electron micrograph of our initial fabricated 50-µm-size active square micropillar resonator integrated with a lateral p-i-n diode on a SOI substrate. Here we employ round-cornered square micropillar resonator configuration [5]. The silicon device layer is p-type with a doping of 10^{15} cm^{-2}. We apply ion implantation to form the n-doped (1×10^{20} cm^{-2} phosphorous ions) region and the p'-doped (2×10^{19} cm^{-2} boron ions) region in the ~50-nm-thick slab layer outside the square micropillar resonator. Thereby the p-i-n diode injects current to the entire intrinsic square micropillar cavity. The highly-doped regions (and their metal electrodes) are separated from the square micropillar sidewall by 1 µm in order to avoid excess absorptive and scattering losses. A ~0.6-µm-thick low-temperature oxide layer was deposited as the device upper-cladding and electrical isolation layer.

Figure 4b shows the measured TE-polarized throughput-port spectra of the active square micropillar resonator-based switch at an OFF-state (solid-line) and an ON- (with a driving voltage V_d = 4V, dashed-line). We observe only two distinct modes with a maximum extinction ratio of ~17 dB and a Q of ~1,500. The measured FSR is ~4.7 nm, consistent with the calculated FSR of ~4.9 nm by assuming 4-bounce ray orbits with θ ~ 45° and n ~ 3.5. By applying a 4 V forward-bias driving voltage, we obtain a resonance wavelength blueshift of ~0.54 nm. The reduction in the resonance extinction ratio is attributed to the accompanied free-carrier absorption. At a probe wavelength of ~1553.8 nm, we obtain an intensity ratio of ~11.3 dB between the ON- and OFF-states, thus providing a resonance-based large-extinction-ratio switching.
However, our initial active square micropillar resonator-based device design is not optimized for high-speed modulator applications. Figure 4c shows the measured 3-dB modulation bandwidth of only ~2 MHz at mode A. Inset shows the driving electrical waveform and the resulting optical waveform near mode A measured at 500 kHz modulation frequency. We measure a 10%-to-90% rise time of ~ 357.4 ns and a 90%-to-10% fall time of ~ 407.4 ns. We attribute the slow electro-optic response to the 50-µm-wide intrinsic region of the p-i-n diode.

5. CONCLUSIONS

In summary, we analyzed and demonstrated silicon-based waveguide-coupled square microresonator-based devices including channel filters and electro-optic switches. Our two-dimensional finite-difference time-domain simulations and Fourier analysis showed that lateral waveguide coupling to planar microstructures with a long flat coupling sidewall enables directional k-vectors in the coupled microstructures. The directional k-vectors thus potentially give rise to preferentially coupled modes in large-size square micropillar resonators. Our initial experiments on silicon-on-insulator waveguide-coupled large-size square micropillar resonators demonstrated only 2 – 3 modes. It appears to be instrumental to tailor the square cavity shape by cutting or rounding the cavity corners. We also experimentally demonstrated injection-type square micropillar resonator-based silicon electro-optic switches using integrated lateral p-i-n diodes. We obtained a resonance wavelength blueshift of ~ 0.54 nm under 4 V forward bias. The device 3-dB bandwidth is only ~ 2 MHz, possibly limited by the wide intrinsic region width (~ 50 µm) of the square p-i-n diode structure. Further design, fabrication, and characterization of silicon square micropillar resonator-based passive and active devices are in progress.

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REFERENCES