Laterally coupled hexagonal micro-pillar resonator add-drop filters in silicon nitride

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Abstract—We report the first laterally coupled hexagonal micro-pillar resonator add-drop filters in silicon nitride. Our experiment reveals waveguide-coupled resonances of 6-bounce ray orbits in the hexagonal microcavity. By tuning the sub-micrometer waveguide width, we demonstrate simultaneous optimization of the coupling efficiency and the resonance Q value. We attribute the optimum waveguide width to the near k-vector matching between the input and output-coupled waveguide fundamental mode and the cavity 6-bounce modes that are coherently coupled along the resonator flat sidewalls.

Index Terms—micro-pillar resonators, microcavity, add-drop filters, integrated photonic circuits, silicon-based photonics, wavelength-division multiplexing.

I. INTRODUCTION

Laterally waveguide-coupled circular disk and ring micro-pillar (μ -pillar) resonators have been widely investigated for add-drop applications in wavelength-division multiplexing (WDM) communications [1]–[3]. However, the short interaction length between the resonator curved sidewall and the evanescently coupled straight waveguide sidewall imposes a technological challenging sub-micrometer air-gap separation between the resonator and the waveguide. In order to increase the interaction length, racetrack microring resonators that have two parallel straight sections have long been proposed for side coupling with straight waveguides [4]. However, racetrack resonators can have considerable cavity loss due to the modal mismatch at the junctions between the straight sections and the 180°-curved sections, particularly when the resonator size approaches a few μm [4]. The racetrack microring inner sidewall also imposes considerable scattering loss.

Recently, polygonal μ -pillar resonators in the form of square [5] – [7], hexagon [8,9], and octagon [10] that are comprised of flat resonator sidewalls with no curved sections or inner sidewalls have been proposed as alternative resonators to

increase the interaction length for the lateral coupling. These N-polygonal resonators have N-bounce closed or open ray orbits that can be wavefront matched [5] – [10]. Ray orbits of the same wavefront-matched path lengths can be coupled along almost the entire resonator sidewalls [6, 9]. Compared with racetrack type resonators, polygonal μ -pillar resonators can be more favorable for fabrication because of the flat sidewalls. Polygonal μ -pillar resonators also eliminate the racetrack straight-to-bending waveguide loss, the waveguide bending loss, and the inner sidewall scattering loss. However, polygonal μ -pillar resonators can have undesirable cavity corner leakage [10]. The principle of mode coupling between side-coupled waveguides and polygonal μ -pillar resonators [5, 7, 9, 10] also requires further theoretical development.

In this letter we report, for the first time to our knowledge, laterally waveguide-coupled hexagonal μ -pillar resonator add-drop filters in silicon nitride. Our experiment reveals waveguide-coupled resonances of 6-bounce ray orbits in the hexagonal μ -pillar resonator. We simultaneously optimize the cavity mode coupling and the resonance Q by tuning the sub-micrometer waveguide width.

II. DEVICE PRINCIPLE

Fig. 1 shows a schematic of the laterally waveguide-coupled hexagonal μ -pillar resonator add-drop filter. The parallel input and output-coupled waveguides have the same width w and are separated from the resonator by an air-gap spacing g . The hexagonal resonator has a sidewall-to-sidewall distance a . The waveguides and the resonator have the same material refractive index n . We denote the input and output-coupled waveguide fundamental mode propagation vector as $\mathbf{k}_{\text{wg}}$ and the propagation angle relative to the waveguide sidewall normal as Φ . We also denote the cavity mode propagation vector as $\mathbf{k}_{\text{cav}}$ ($\mathbf{k}_{\text{cav}}'$) and the propagation angle as θ ($\gamma = 120^\circ - \theta$) at the input-coupled (output-coupled) sidewall.

Here, we only consider modes with 6-bounce ray orbits near $\theta = 60^\circ$ [9]. For $\theta = 60^\circ$ ($\gamma = \theta$), the ray orbits are closed and can form an infinite number of round trips. Such closed-orbit resonances are expected to be relatively high-Q. For $\theta \neq 60^\circ$ ($\gamma \neq \theta$), the ray orbits are open and can only circulate for a limited number of round trips (depending on θ and the ray initial positions) before the ray displaced to the adjacent sidewall and refractively escapes. Such open-orbit resonances are expected to be relatively low-Q.

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By tuning w , ray orbits of different θ 's can be selectively input and output-coupled [7]. Here we assume that $\mathbf{k}_{wg} \approx \mathbf{k}_{cav}$ and $\Phi \approx \theta$ at the input coupling, while $\mathbf{k}_{wg} \approx \mathbf{k}_{cav}'$ and $\Phi \approx \gamma$ at the output coupling. The near $\mathbf{k}$ -vector matching is due to the coupling between the waveguide and the finite-size microcavity. Considering the parallel input and output-coupled waveguides of the same width, we reason that only the $\theta \approx \gamma \approx 60^\circ$ 6-bounce high-Q modes can be simultaneously (near) $\mathbf{k}$ -matched and coupled at both the input and the output-coupled waveguides.

Fig. 1. Schematic of a laterally waveguide-coupled hexagonal μ -pillar resonator add-drop filter. I: Input, T: Throughput, D: Drop, A: Add.

Multiple ray orbits of the same θ (i.e. the same wavefront-matched path lengths [8,9]) can be input and output-coupled along resonator flat sidewalls. Number of coupled ray orbits of the same θ depends on w and the sidewall length. Fig. 1 illustrates two closed ray orbits input and output-coupled along the resonator sidewalls. The two ray orbits are mutually coupled through the input and output-coupled waveguides. It is expected that these resonance ray orbits of same path lengths coupled along the resonator flat sidewalls can enhance the coupling efficiency. We also expect that these coherent wavefront-matched ray orbits can interfere constructively at the drop port, and destructively at the throughput port. This multiple interference between coherent ray orbits of same path lengths can then result in an increase in the cavity finesse.

III. EXPERIMENTAL RESULTS

We employed standard silicon microfabrication processes as detailed in [10]. The device was comprised of a 1.1- μm thick low-stress silicon nitride (SiN) film on a 1.5- μm thick silica under-cladding. The stack-layered structure was air-clad. The device pattern was defined by photolithography and transferred onto the nitride layer by plasma etching. The etched rib waveguides and resonators have a slab height about 0.2 μm and a slope angle of about 84° (due to the plasma etching).

Fig. 2 (a) shows a top-view electron micrograph of a fabricated device with $a \approx 50 \mu\text{m}$, $w \approx 0.50 \mu\text{m}$, and $g \approx 0.35 \mu\text{m}$. The drop waveguide is 180° bent with a 100- μm radius of curvature for the ease of measurement. Fig. 2 (b) – 2 (e) depict four top-view electron micrographs of the

waveguide-gap-cavity region with $w \approx 0.45 \mu\text{m}$, $0.5 \mu\text{m}$, $0.55 \mu\text{m}$ and $0.60 \mu\text{m}$, all have $g \approx 0.35 \mu\text{m}$.

The device characterization employed conventional laser wavelength-scanning technique as detailed in [10]. A wavelength-tunable diode laser (1510 nm – 1580 nm wavelength) was end-fired to the input-port using a tapered polarization-maintaining singlemode fiber. The chip edges were cleaved and unpolished. Fig. 2 (f) shows the measured TM-polarized ($\mathbf{E} \perp$ the chip) throughput (dark line) and drop (gray line) spectra of the fabricated device with $w \approx 0.50 \mu\text{m}$. The throughput and drop-port intensity is normalized with the tapered fiber transmitted intensity. We observed an almost single set of resonances with finesse about 6. The measured free spectral range (FSR) is about 7.7 nm, which is consistent with the calculated FSR of a 6-bounce wavefront-matched orbit assuming $\theta \approx 60^\circ$ and $n \approx 2$ for SiN [8]. The ripples in the spectra are due to the waveguide-end reflections.

At resonance 1555.24 nm, we obtained a $Q \approx 1,300$, a coupling efficiency exceeding 98%, a drop-port extinction ratio about 11 dB, a drop-efficiency about 30%, and an on-off ratio about 14 dB. We define the coupling efficiency as the ratio of the depth of the throughput resonance dip to the off-resonance intensity. We define the drop efficiency as the ratio of the drop resonance peak to the throughput off-resonance intensity. Inset shows the top-view optical micrograph of the scattering intensity at the same resonance. This on-resonance image reveals pronounced light scattering near the cavity corners, suggesting that resonance ray orbits impinged on all the six cavity sidewalls and having a considerable leakage at the cavity corners. We remark that by rounding the cavity corners, the cavity corner leakage can be mitigated [9].

Fig. 2. (a) Top-view electron micrograph of the fabricated filter with $a \approx 50 \mu\text{m}$, $w \approx 0.50 \mu\text{m}$, $g \approx 0.35 \mu\text{m}$. (b) - (e) Four top-view electron micrographs of the waveguide-gap-cavity region with $w \approx 0.45 \mu\text{m}$, $0.5 \mu\text{m}$, $0.55 \mu\text{m}$, and $0.6 \mu\text{m}$, with $g \approx 0.35 \mu\text{m}$. (f) Measured TM-polarized throughput (dark line) and drop (gray line) spectra for the filter with $w \approx 0.50 \mu\text{m}$. Inset shows the top-view optical micrograph of the scattering intensity at resonance 1555.24 nm.

Fig. 3. (a) – (e) Measured TM-polarized spectra for $w \approx 0.40 \mu\text{m}$, $0.45 \mu\text{m}$, $0.5 \mu\text{m}$, $0.55 \mu\text{m}$, and $0.6 \mu\text{m}$. (f) Measured coupling efficiency varies with w for both TM ($\sim 1555 \text{ nm}$) and TE ($\sim 1559 \text{ nm}$) polarization. (g) Measured Q factor varies with w for TE only. Four insets show the TE-polarized spectra for $w \approx 0.55 \mu\text{m}$, $0.6 \mu\text{m}$, $0.65 \mu\text{m}$, and $0.7 \mu\text{m}$. (h) Calculated slab waveguide fundamental mode angle Φ varies with w for both TM and TE polarization at 1510 nm (solid line) and 1580 nm (dashed line) wavelengths.

We measured the off-resonance throughput-port transmission for $w \approx 0.50 \mu\text{m}$ to be about -14 dB for TM polarization (Fig. 2 (f)), and near -20 dB for TE polarization (not shown). Using control waveguides of different lengths fabricated on the same chips, we measured the $0.5\text{-}\mu\text{m}$ waveguide propagation loss in the 1510 nm - 1580 nm wavelengths to be 13 dB/cm - 9 dB/cm (TM), and 10 dB/cm - 13 dB/cm (TE). For the input waveguide length of about 3.47 mm , we estimated the waveguide propagation loss to be 4.5 dB - 3.1 dB (TM) and 3.5 dB - 4.5 dB (TE). From the measured off-resonance transmission and the estimated waveguide propagation loss, we estimated the off-resonance insertion loss to be 9.5 dB - 10.9 dB (TM) and 16.5 dB - 15.5 dB (TE).

We measured various devices ($a \approx 50 \mu\text{m}$, $g \approx 0.35 \mu\text{m}$) with different waveguide width w . Fig. 3 (a) – 3 (e) show the TM-polarized throughput resonance dips with $w \approx 0.4 \mu\text{m}$, $0.45 \mu\text{m}$, $0.5 \mu\text{m}$, $0.55 \mu\text{m}$, and $0.60 \mu\text{m}$. Both the coupling efficiency and the resonance Q for TM modes are optimized at $w \approx 0.50 \mu\text{m}$. We remark that the spectra for $w \approx 0.45 \mu\text{m}$ (Fig. 3 (b)) and $w \approx 0.55 \mu\text{m}$ (Fig. 3 (d)) have two resonances that are inhomogeneously broadened, which can impose uncertainties in our analysis.

Insets (i) – (iv) in Fig. 3 (g) show the TE-polarized throughput resonance dips with $w \approx 0.55 \mu\text{m}$, $0.60 \mu\text{m}$, $0.65 \mu\text{m}$, and $0.7 \mu\text{m}$. Both the coupling efficiency and the resonance Q for TE modes are optimized at $w \approx 0.65 \mu\text{m}$. Fig. 3 (f) shows the analysis of the measured resonance coupling efficiency varies with w for both TM and TE polarization. Fig. 3 (g) shows the measured resonance Q varies with w for TE polarization only.

The relatively high coupling efficiency and resonance Q at a polarization-dependent optimum waveguide width can be attributed to the near $\mathbf{k}$ -vector matching between the input and output-coupled waveguides and the $\theta \approx 60^\circ$ modes. Fig. 3 (h) shows the calculated slab waveguide (with $n = 2$) fundamental mode propagation angle Φ varies with waveguide width w , for both TM and TE polarization at 1510 nm (solid line) and 1580 nm (dashed line) wavelengths. For TM case, we calculated $\Phi \approx 60.8^\circ$ - 61.6° at $w \approx 0.50 \mu\text{m}$. For TE case, we obtained $\Phi \approx 57.8^\circ$ - 59.1° at $w \approx 0.65 \mu\text{m}$. The calculated Φ 's are consistent with 6-bounce $\theta \approx 60^\circ$ modes. We remark that the polarization sensitivity can be partially compensated by tailored waveguide or resonator profiles (e.g. by adding a thin-film birefringent upper-cladding).

IV. CONCLUSIONS

In summary, we experimentally demonstrate the first to our knowledge laterally waveguide-coupled hexagonal μ -pillar resonator add-drop filters in silicon nitride. By tuning the waveguide width, we demonstrate that both the resonance coupling efficiency and the resonance Q can be simultaneously optimized. We expect that laterally waveguide-coupled silicon-based hexagonal μ -pillar resonators can be important for add-drop filters and high-density integrated photonic circuits.

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