Spiral-shaped microdisk resonator-based channel drop filters on a silicon nitride chip

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Abstract: We demonstrate spiral-shaped microdisk resonator-based channel drop filters on a silicon nitride chip. Our experiments reveal multiple resonance modes that are sensitive to the laterally coupled waveguide angular positions along the non-rotational symmetric microresonator circumference.

OCIS codes: (230.5750) Resonators; (230.3990) Microstructure devices

Planar microresonators of various cavity shapes including circular disk [1] and ring [2], racetrack ring [3], and polygons [4] have been recently demonstrated as filters and switches on silicon-based substrates. These conventional cavity shapes preserve certain degree of rotational symmetry, and thus the light input and output coupling is generally not sensitive to the sense of cavity lightwave circulation. Recently, Chern et al. [5] proposed spiral-shaped disk microcavities that are non-rotational symmetric, with the radius linearly varies with azimuthal angle, and demonstrated unidirectional lasing from InGaN spiral-shaped micropillar cavities with laser emission out-coupling from the spiral notch. Inspired by the prospect of exploiting unidirectional out-coupling characteristics for novel devices, here we report our initial experimental demonstration of spiral microdisk resonator-based channel drop filters on a silicon nitride chip. We show that spiral-shaped microcavity modes are sensitive to the laterally coupled waveguide angular positions along the non-rotational symmetric cavity circumference.

Fig. 1. (a) Top-view schematic of the spiral-shaped microdisk resonator-based channel drop filters. The spiral shape is defined as \( r(\phi) = r_0 (1 - \varepsilon \phi / 2\pi) \). cw: clockwise, ccw: counterclockwise, I: Input, T: Throughput, D: Drop.

(b),(c) Scanning electron micrographs of our fabricated devices on a silicon nitride-on-silica substrate with the in-coupled waveguide at angular positions of (b) \( \phi = \pi \), and (c) \( \phi = 5\pi/4 \). \( w = 0.4 \mu m \), \( g = 0.4 \mu m \), \( r_s = 25 \mu m \), and \( \varepsilon = 0.016 \).

Figure 1(a) shows the schematic of the spiral microresonator-based channel drop filter. The spiral shape is defined as [5]

\[
  r(\phi) = r_0 \left( 1 - \frac{\varepsilon \phi}{2\pi} \right).
\] (1)
where \( r_0 \) is the spiral radius at azimuthal angular position \( \phi = 0 \), and \( \varepsilon \) is the deformation parameter. The radius linearly reduces with \( \phi \). The mismatch in radius at \( \phi = 2\pi \) gives a notch of width \( r_0\varepsilon \). The spiral notch is seamlessly butt-coupled to a waveguide of the same width for channel dropping. Lightwave is evanescently in-coupled to the microresonator from a lateral waveguide of width \( w \) at an angular position \( \phi \). Thus, the clockwise (cw) mode is in the preferred sense of circulation for out-coupling to the notch-coupled waveguide acting as the drop-port, whereas the counterclockwise (ccw) mode is not favorable for out-coupling through the spiral notch. We remark that the notch-coupled waveguide enables lightwave to be out- or in-coupled to the spiral microresonator from the notch without relying on evanescent field. Here we experimentally study the throughput and drop-port spectra of the cw and ccw modes, by means of in-coupling lightwave to the microresonator at two arbitrarily chosen laterally coupled waveguide angular positions \( \phi = \pi \) and \( \phi = 5\pi/4 \).

Figures 1(b) and 1(c) show the top-view scanning electron micrographs of our initial fabricated spiral microresonator-based channel drop filters with lateral waveguides coupled at \( \phi = \pi \) and \( \phi = 5\pi/4 \) on a silicon nitride-on-silica substrate (1.1 \( \mu \)m device layer on 1.5 \( \mu \)m silica under-cladding). The \( r_0 \) is \( \sim 25 \) \( \mu \)m and \( \varepsilon \) is \( \sim 0.016 \). Both the notch-coupled and lateral waveguides have the same width of \( \sim 0.4 \) \( \mu \)m and an etched height of \( \sim 1.0 \) \( \mu \)m. The gap separation between the lateral waveguide and the spiral cavity curved sidewall is \( \sim 0.4 \) \( \mu \)m. In order to allow simultaneous measurements of both the throughput and drop-port spectra for the cw mode, the drop-port waveguides are 180°-bend (with a large 50-\( \mu \)m radius of curvature) towards the throughput-port direction.

![Figure 2](image.png)

Figure 2. (a)-(d) Measured TM-polarized throughput- and drop-port spectra for the cw and ccw modes with the lateral waveguide coupled at \( \phi = \pi \). The intensity is normalized with the transmission light intensity from the singlemode polarization-maintaining lensed-tapered fiber launching light into the tapered input-port. (a) Throughput-port spectrum for the cw mode. (b) Drop-port spectrum for the cw mode. (c) Throughput-port spectrum for the ccw mode. (d) Transmission spectrum in-coupled from the notch-coupled waveguide.

Figures 2(a) and 2(b) show the measured TM-polarized (electric-field \( \perp \) plane) throughput- and drop-port spectra of the spiral microresonator cw mode with the in-coupled waveguide positioned at \( \phi = \pi \). Figure 2(c) shows the measured TM-polarized throughput-port spectrum of the ccw mode (on the same device). The cw and ccw modes exhibit the same multiple modes throughput-port spectra. Typical free-spectral range (FSR) is \( \sim 7.1 \) nm that is consistent with the spiral microcavity circumference, suggesting that the resonance lightwave essentially grazes along the asymmetrical microcavity rim as in whispering-gallery modes of a circular microcavity. We measure a Q-factor of \( \sim 5000 \) at a resonance wavelength of 1533.7 nm. However, we note that the drop-port resonance peak intensity is only about an order of magnitude below the throughput-port off-resonance intensity in the cw mode. We attribute this to possibly large scattering losses at a yet-optimized notch junction design in our initial devices.
Figure 2(d) shows the measured TM-polarized transmission spectrum at the lateral waveguide input-port with the light launched from the notch-coupled waveguide. We find that the notch-coupled resonances are identical to the laterally coupled resonances and display similar resonance peak intensities, suggesting that the notch-coupled waveguide can act as an in-couple waveguide without the complication of an evanescent field.

![Figure 3](image)

Figure 3. (a), (b) Measured TM-polarized (a) throughput and (b) drop-port spectra for the cw mode with the lateral waveguide coupled at $\phi = 5\pi/4$ (dark line). The $\phi = \pi$ drop-port spectrum (gray line) is overlaid in (b).

Figures 3(a) and 3(b) show the measured TM-polarized throughput- and drop-port spectra of the cw mode with the lateral waveguide coupled at $\phi = 5\pi/4$. Comparing with the $\phi = \pi$ spectra, we see that the $\phi = 5\pi/4$ spectra display a different set of resonances while preserving the same $\text{FSR} \approx 7.1 \text{ nm}$. Figure 3(b) also depicts an overlaid $\phi = \pi$ (gray line) drop-port spectrum. We observe that mode A from $\phi = \pi$ coupling are suppressed at $\phi = 5\pi/4$ coupling. Whereas mode B is preferentially coupled from $\phi = 5\pi/4$, yet not evident from $\phi = \pi$ coupling. In both cases, mode C is similarly coupled. The implication is that the resonances in the non-rotational symmetric spiral microdisk can be selectively coupled from different azimuthal angles, thus enabling novel devices for directional resonant lightwave routing. In contrast, resonances in the conventional circular microresonator can only be symmetrically coupled along the cavity circumference.

In summary, we demonstrated spiral-shaped microdisk resonator-based channel drop filters on a silicon nitride-on-silica substrate. We observed channel drop functionality by directly out-coupling resonance channels from the spiral notch-coupled waveguide. We showed azimuthal angle dependent resonance coupling, which is unique to non-rotational symmetric microcavities. We believe that the spiral microdisk offers a new way to directionally route resonant lightwave channels on a silicon chip.

References