Measurement of Multimode Resonances in Hexagonal Micro-Pillar Optical Cavities

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I. Introduction
Optical micro-pillar (μ-pillar) resonators have attracted recent interests for potential applications in integrated photonics due to their compact size (of 10 - 100 μm lateral dimensions and of ~ μm height) and high-Q resonances. Ring and disk μ-pillar wavelength-division multiplexing (WDM) channel add/drop filters have been demonstrated [1]. Very large-scale integrated (VLSI) photonic chips using μ-pillar cavities are feasible [2]. High-Q optical resonances can be confined by nearly total internal reflection (TIR) at the μ-pillar resonator sidewall. The μ-pillar cavity can be evanescently side-coupled or vertically coupled [3] to input and output waveguides. The main drawback of the conventional side-coupled circular ring and disk cavities is the short interaction length between the curved cavity sidewall and the straight waveguide sidewall. Such short interaction length imposes a sub-micrometer gap distance for evanescent coupling.

Polygonal μ-pillar resonators provide an alternative means of increasing the evanescent side-coupled length for potential WDM add/drop filter applications [4]. The advantages of the polygonal cavities are twofold: (1) The entire flat polygonal sidewall allows a longer interaction length, and therefore a wider gap distance for evanescent coupling between the cavity and the straight waveguides; and (2) the optical path length is identical for rays having the same incident angle along the sidewall, and hence the same cavity mode can be coupled anywhere along the flat sidewall. Fabrication of polygonal μ-pillar cavities can be readily achieved with established microelectronic fabrication processes. Recently, multimode resonances in square-shaped μ-pillar cavities were demonstrated [4], and hexagonal microlasers have been reported [5].

In this paper, we report our recent measurement of multimode resonances in the elastic-scattering spectrum of hexagonal μ-pillar optical cavities, using Gaussian beam coupled along the cavity sidewall. The observed free spectral range (FSR) is consistent with the six-bounce closed-loop path length. By using the wavefront-matching concept [4], the observed multimode resonances can be attributed to round-trip trajectories that need not be closed after each round trip.

II. Ray Optics in Hexagonal Cavities
Figure 1 (a) shows the six-bounce closed-loop trajectories with an incident angle θ = 60°. All hexagonal orbits with θ = 60° (such as the solid and dashed lines) have the same path length of 3L (L is the distance between two parallel planes) and therefore have the same cavity modes. Trajectories with θ ≠ 60° do not close upon themselves in each round trip. Figure 1 (b) shows the six-bounce open-loop trajectory with incident angle θ ≠ 60°, and a complementary incident angle 120° - θ at the adjacent sidewall. For the trajectory to be confined by TIR, θ needs to satisfy θc < θ < 120° - θc, where the critical angle θc = sin⁻¹(1/n), and n is the refractive index of the dielectric cavity in air. In silica n ≈ 1.44 (λ ≈ 1.5 μm), and
$\theta_c \approx 44^\circ$, $44^\circ < \theta < 76^\circ$. In the cavity, the incident wavefront and the wavefront of the open-loop round trip ray can be spatially overlapped, as shown by the dashed line in Figure 1 (b). Following the discussion of multimode resonances in square µ-pillar cavities in [4], we believe such wavefront-matched open round trip can result in multimode resonances in hexagonal cavities.

III. Experiment and Results

A commercially available hexagonal silica fiber was employed in the elastic-scattering experiment. The fiber was side-couple perpendicular by a Gaussian beam, and thus acted as an optical µ-pillar cavity. Two fiber sizes with $L = 125 \ \mu m \pm 2.5 \ \mu m$ and $L = 200 \ \mu m \pm 4 \ \mu m$ were used in the experiment. The fiber corners are slightly rounded. The fiber orientation was monitored with an uncertainty of $\pm 2^\circ$ by a top-view microscope. A Gaussian beam from a wavelength-tunable diode laser (1510 nm – 1580 nm-wavelength range) was weakly focused (by a $f/20 \sim f/33$ cylindrical lens) to the fiber and tangentially onto the fiber flat sidewall. The line beam was along the fiber axis. The estimated beam width was $\approx 100 \ \mu m$. The incident polarization was parallel to the fiber axis (TM mode). We tuned the separation between the line beam and the fiber sidewall in order to excite the cavity modes. The elastic-scattering spectrum was imaged (with an acceptance angle of $2.6^\circ$) from the fiber flat sidewall onto an InGaAs photodiode. An analyzer was placed in front of the photodiode to measure the TM spectrum. The laser linewidth is $\approx 2 \times 10^{-6} \ nm$, and the spectral resolution was 0.003 nm. Figure 2 shows the schematic of the hexagonal fiber side-coupled with a Gaussian beam.

Figure 3 shows the measured TM polarized elastic-scattering spectrum of a $L = 200 \ \mu m$ hexagonal fiber imaged at $60^\circ$ from the Gaussian beam direction. The highest measured Q factor is $> 2000$. The spectrum is multimode. At least four orders of modes were observed (labeled as A, B, C, D) with a FSR $\approx 2.8 \ nm$. The scattering spectra at other angles were also measured.
Assuming a six-bounce closed-loop trajectory, the FSR is calculated as follows:

\[
FSR \approx \frac{\lambda^2}{3nL}
\]

where \( \lambda \approx 1550 \text{ nm} \), \( n = 1.44 \), \( L = 200 \mu \text{m} \), and \( 3L \) is the closed-loop path length. The calculated FSR \( \approx 2.78 \text{ nm} \) is consistent with the measured FSR \( \approx 2.8 \text{ nm} \).

Figure 3 Measured multimode resonances (at 60º scattering angle) in a TM-polarized elastic-scattering spectrum of a hexagonal optical fiber (\( L = 200 \mu \text{m} \)). The FSR is ~ 2.8nm. The inset shows a schematic of the Gaussian beam (the thick arrow) grazing the hexagonal fiber sidewall and a six-bounce closed-loop trajectory.

Figure 4 Measured multimode resonance in a TM-polarized elastic-scattering spectrum of a hexagonal optical fiber (\( L = 125 \mu \text{m} \)) at 60º scattering angle. The FSR is ~ 4.4 nm.
Figure 4 shows the measured TM polarized scattering spectrum at 60° in a 125 μm hexagonal fiber. The observed FSR ≈ 4.4 nm is consistent with the calculated FSR ≈ 4.45 nm by means of equation (1). There are more than 4 orders of modes. By further reducing the cavity dimensions, larger FSR is expected, which is an essential requirement for WDM add/drop filter applications. In order to obtain a FSR > 30 nm, which spans the 1.55 μm telecommunication window, a silica hexagonal μ-cavity with L < 20 μm is needed. Such small μ-pillar cavities can be readily fabricated by microelectronic technologies.

In summary, the elastic-scattering spectra of hexagonal μ-pillar resonators were measured. The multimode resonances can be attributed to the wavefront-matched open-loop trajectories. A smaller-sized hexagonal cavity coupled with waveguides has potential applications in WDM add/drop filters.

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References