Single order resonances of square micro-pillar cavities by prism coupling

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Abstract

Single order resonances of large-sized square micro-pillar cavities have been measured by using prism coupling with over 60% coupling efficiency. We have qualitatively compared the observed single order resonances with 2-D finite-difference time-domain (FDTD) simulation of a micron-sized square micro-cavity coupled with a planewave illuminated dielectric flat interface in close proximity. A coupling efficiency of over 70% can be attained in a selected range of incident angles near the critical angle of total internal reflection. The FDTD square micro-cavity resonance field distribution reveals a periodic array of field extrema, which can be attributed to K-space modes.

1. Introduction

Micro-sized optical resonant cavities in the form of circular pillar or ring have been of increasing interest for photonic integrated circuits (PICs) applications due to the cavity compact size and high-Q resonances [1, 2, 3, 4]. Waveguide laterally-coupled circular disk or ring micro-cavities have been studied by many investigators [1, 3]. However, the shortcoming of circular micro-pillar (µ-pillar) resonators is that the curved cavity sidewall only has a short interaction length with the flat lateral coupler such as a straight waveguide.

Recently, square µ-pillar resonators have been proposed for improved lateral coupling due to the long interaction length along the entire flat cavity sidewall [5, 6, 7]. Multimode high-Q resonances of a large-sized square µ-pillar cavity have been measured by Gaussian beam coupling [6] and by prism coupling [7]. In the former case, the coupling can only be partially tuned by changing the laser beam profile and the separation between the cavity sidewall and the Gaussian beam axis [6]. In the later case, the coupling was mostly tuned by varying the submicrometer air-gap spacing between the prism and the cavity [7].

Here we report our preliminary measurement of single order resonances of a large-sized square µ-pillar cavity by prism coupling. The experiment was qualitatively compare with a 2-D FDTD simulation of a micron-sized square µ-cavity coupled with a planewave illuminated dielectric flat interface in close proximity. A periodic array of field extrema was observed in the FDTD simulated square µ-cavity resonance field pattern. We attribute the field extrema distribution to K-space modes.

2. Experiment

Figure 1 illustrates a schematic of the experimental setup. A large-sized square µ-pillar cavity (with plane-to-plane distance $L \approx 200 \mu m$ and rounded corners) in the form of a commercially available square silica optical fiber (with refractive index $n \approx 1.44$) was evanescently coupled with a hemi-cylinder silica prism (with refractive index $n \approx 1.44$) was evanescently coupled with a hemi-cylinder silica prism in close proximity. A wavelength-tunable external-cavity diode laser (with a laser linewidth $\approx 300$ kHz in the wavelength range 1510 nm - 1580 nm,) was weakly focused by a f/25 cylinder lens onto the central region of the prism-fiber interface, at an incident angle $\theta$ larger than the critical angle $\theta_c = \sin^{-1}(1/1.44) = 44^\circ$. The line of laser beam was parallel to the fiber axis and allowed $\approx 4$ mm of fiber length to be evanescently coupled simultaneously. The laser was TE-polarized (with the E-field perpendicular to the fiber axis). The prism was mounted on a mechanical stage that has translation, rotation (with an angular resolution $\approx 0.04^\circ$)

![Fig. 1. Schematic of the square fiber prism coupling experiment.](image)
and tilt (with an angular resolution $\approx 0.02^\circ$) degree of freedom. The square fiber was positioned on another mechanical stage, which can rotate (with an angular resolution $\approx 2^\circ$) and translate along the x and z-axis. The translation stage along z is driven by a piezoelectric motor (with a resolution $< 30$ nm) to bring the fiber to within a submicrometer distance from the prism flat surface. A top-view CCD camera monitored the relative orientation of the fiber and the prism. A side-view CCD camera monitored the relative fiber tilting (with an angular resolution $\approx 0.03^\circ$). The frustrated total internal reflection (FTIR) was lock-in detected by using a photodiode detector after an analyzer.

Figure 2 shows the preliminary measured TE-polarized FTIR spectrum ($\approx 0.03$-nm resolution) of the square µ-pillar cavity at $\theta \approx 45^\circ$ (with alignment uncertainty of $\approx \pm 2^\circ$). The spectrum reveals a preferentially coupled single order resonances with a coupling efficiency (defined as the percentage of intensity drop at resonance) exceeds 60%. We attribute this observation of single order resonances to the preferential coupling of the weakly focused laser beam at a particular resonance mode angle. The resonances have a $Q \approx 5,500$. The measured free spectral range (FSR) $\approx 2.8$ nm is consistent with that of a 4-bounce cavity round-trip trajectory $[6] = \frac{\lambda^2}{(n L 2\sqrt{2})} \approx (1535*10^{-9})^2/(1.44*2*10^{-7}*2\sqrt{2}) \approx 2.9$ nm. The ripples in between the resonances are due to the etalon effect in the diode laser cavity.

3. FDTD Simulation

In order to numerically study the prism coupling to a square µ-pillar cavity, we employed a commercially available 2-D FDTD tool [8] to simulate a micron-sized square µ-cavity coupled with a planewave illuminated dielectric flat interface in close proximity. Figure 3 depicts the preliminary simulation layout. In our simulation, a square µ-cavity of $L = 7$ µm was laterally coupled to a 4 µm x 14 µm rectangular dielectric block (prism) via an air-gap spacing of 0.4 µm. A refractive index contrast $n = 1.44$ was assumed. A single 5.17-fs light pulse centered at vacuum wavelength 1.55 µm was launched onto the prism-cavity interface at $\theta$ in the neighborhood of $\theta_c$. The incident wave was modeled as a fundamental slab waveguide mode with a 7-µm width, in order to attain a plane wavefront that has a small angular spread of $\approx 7^\circ$. For 4-bounce trajectories, the incident light ray should satisfy the condition $\theta_c < \theta < 90^\circ - \theta_c$. The incident light was TM polarized (E-field $\perp$ plane of incidence). A 0.02-µm grid size and a 0.04-fs time step were adopted. A 0.5-µm perfectly matched layer (PML) boundary of reflectivity $10^{-8}$ was used. The three outer boundaries of the prism were positioned at the PML boundaries. The source, the FTIR, the internal field and the sidewall-transmitted field were monitored over the region a (with width 6 µm), b (6 µm), c (3.5 µm) and d (1.5 µm). The solid and dashed arrows represent the incident, reflected ray in the prism and the round-trip trajectories in the cavity.

Figure 4(a) shows the preliminary FDTD-calculated FTIR (solid) and the sidewall-transmitted (dashed) input-normalized spectrum at $\theta = 43^\circ$, $45^\circ$ and $47^\circ$. The spectra reveal single order resonances at the same
wavelengths. The FSR in the 1.5 µm wavelength window is ≈ 80 nm, which is consistent with the FSR of a 4-bounce cavity round-trip trajectory \[ \approx \lambda^2 / (\pi L) \approx (1500*10^{-9})^2 / (1.44*7*10^{-6})*2 \approx 79 \text{ nm} \]. The reflected spectra show an increasing intensity with 0, while the sidewall-transmitted spectra are decreasing with 0. Figure 4(b) shows a high coupling efficiency of over 70% at the 1.47µm resonance.

Figure 5 shows the preliminary FDTD simulated ‘chessboard’-liked resonance field distribution at wavelength 1.47 µm with 0 = 47°. The gray scale represents the field amplitude from -1 to 1. Hindsight, we observed a strong field across the air gap between the square cavity and the prism (shown in the circled region). The strong field is likely due to an unintended refractive leakage of the incident wave that has a noticeable angular spread. When the refractive-coupled field reaches the first-bounded sidewall, total internal reflection (TIR) occurs for \((90°-\theta) > \theta \). At TIR, an evanescent wave normal to the interface and a surface wave along the interface are formed. We can observed a pronounced diffractive leakage of the surface wave along this first-bounced sidewall.

Fig. 4 (a). Preliminary FDTD-calculated FTIR (solid) and sidewall-transmitted spectra (dashed) at \( \theta = 43°, 45° \) and 47°. Fig. 4 (b). Coupling efficiency at different 0 at the 1.47-µm resonance.

Fig. 5. Preliminary FDTD simulated ‘chessboard’-liked resonance field distribution resonance at 1.47 µm with 0 = 47°.

The resonance field distribution shows 10 field amplitude extrema along x and 11 extrema along z inside the cavity. We denoted this field pattern as \((m_x, m_z) = (10, 11)\) mode, where \(m_x, m_z\) are integer number of field extrema along x and z. This \((m_x, m_z)\) field pattern can be attributed to K-space modes [6],

\[
\left( \frac{2\pi \theta}{\lambda} \right)^2 = \left( \frac{\pi}{L} \right)^2 \left( m_x^2 + m_z^2 \right) \tag{1}
\]
We calculated the mode wavelength $\lambda = 1.356 \, \mu m$ for (10, 11) mode with $L = 7 \, \mu m$ and $n = 1.44$. The mode angle can be calculated by,

$$\theta = \tan^{-1}\left(\frac{k_x}{k_z}\right) = \tan^{-1}\left(\frac{m_1}{m_2}\right)$$  

(2)

$\theta = 42.27^\circ$ for the (10, 11) mode. The K-space mode calculation is comparable with the FDTD resonance wavelength. The calculated mode angle also in good agreement with the refractive leakage mentioned.

4. Conclusion

In conclusion, we have demonstrated single order resonances of large-sized square µ-pillar cavity by prism coupling with over 60% coupling efficiency. The measurement was qualitatively compared with 2-D FDTD simulation of a micron-sized µ-cavity coupled with illuminated dielectric flat interface in close proximity. Over 70% of coupling efficiency at resonances can be attained within a selected range of input angles near $\theta_c$. The FDTD resonance field distribution was an array of field extrema that can be attributed to K-space mode.

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References


