Fano resonances in prism-coupled multimode square micropillar resonators

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Abstract: We report Fano resonances in a multimode square glass micropillar resonator using angle-resolved prism coupling. Our experiments reveal characteristically asymmetric lineshapes of high-Q resonances and of detuned low-Q resonances in multimode reflection spectra. The asymmetric resonance lineshapes evolve for an approximately π phase within a 0.5° range of reflection angles. We model our observed asymmetric multimode resonances by the far-field interference between light wave evanescently coupled with a high-Q mode orbit and coherent light wave refractively coupled with a detuned low-Q mode orbit.

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Optical microresonators shaped as sphere, ring, disk, or polygon¹⁻⁵ have been attracting considerable interest for photonic information processing due to their compact size and high-Q resonances. Among these, two-dimensional micropillar (μ -pillar) resonators are particularly suited for nascent high-density integrated photonic circuits. Previously,³ we reported nearly single-mode high-Q resonances in square glass μ -pillar resonators using angle-resolved prism coupling technique. We observed characteristically sharp asymmetric resonances due to the ubiquitous Fano resonance⁶ like interference between a single resonance mode and a coherent background. Such sharp asymmetric resonance lineshapes can have high extinction ratios between the resonance peak and the characteristic Fano resonance “dip,” and thus show good promise for wavelength agile applications in biochemical sensing and in optical switching⁷⁻⁹. Recently, Fano resonances have been reported in various optical resonance configurations including waveguide-coupled microcavities,^{7,8} two-dimensional photonic crystal microcavity,⁹ and spherical Bragg resonators.¹⁰ Among these works,^{3, 7-10} the analyses of Fano resonances only focus on single resonance modes.

Here we report our experiment and theoretical modeling of Fano resonances in multimode resonance spectra of a square glass μ -pillar resonator. We employ angle-resolved prism coupling to resolve the multimode Fano resonance lineshapes evolution in the far-field. We model the multimode asymmetric resonances using multiple-beam interference between light wave evanescently coupled with a high-Q mode orbit and coherent light wave refractively coupled with a detuned low-Q mode.

Inset of Fig. 1 shows two ray orbits of different incident angles θ_A and θ_B coherently prism-coupled with a multimode square μ -pillar resonator. The two ray orbits can be wavefront-matched² at detuned resonance wavelengths λ_A and λ_B . At λ_A (λ_B), light wave coupled with ray

orbit A (B) constitutes a resonance mode, while light wave coherently coupled with ray orbit B (A) gives rise to a background. Fano resonances occur when the light waves from the resonant orbits and the coherent light waves from the off-resonant orbits interfere in the far-field.

The experimental setup (Fig. 1) has been detailed in Ref. [3]. A 200 μm -sized fused-silica square optical fiber with four rounded corner was used as our square μ -pillar resonator. We fixed the square fiber sidewall and the fused-silica prism flat surface in close proximity and non-contact. A Gaussian beam from a wavelength-tunable diode laser was focused with an $f/25$ cylinder lens, forming a line-beam with an estimated cone angle of near 2° and an estimated lateral spot size of about 50 μm in the cylinder prism origin. The incident angle θ was about 45° , near the silica-air critical angle $\theta_c \approx 43.9^\circ$ (silica refractive index $n \approx 1.44$). Such θ favors the input coupling to four-bounce ray orbits in a square μ -pillar resonator.² The prism-reflected light was collimated by another $f/25$ cylinder and was collected by a 62.5- μm core multimode (MM) fiber positioned by a translation stage after an analyzer. The scanning MM fiber (connected with a photodiode) enabled an angle-resolved measurement with an acceptance angle of near 0.03° . The spectral resolution was about 0.02 nm, which was only limited by the wavelength-tuning steps. The angle-resolved measurement is essential to resolve the relative phase between light waves coherently coupled with multimode resonance orbits and interfere in the far-field.

Figures 2 (a) – 2 (e) show the measured TM-polarized ($\mathbf{E}$ -field along the square fiber axis) reflected spectra in the far-field at various θ spanning between about 43.98° and about 43.48° . Multimode asymmetric resonances can be discerned. The lineshapes evolve over an approximately π phase. Mode A has a Q of about 10,000 and mode B has a Q of about 6,500. The free-spectral range (FSR) of mode A is about 2.88 nm and of mode B is about 2.93 nm, both

are consistent with the calculated FSR ≈ 2.95 nm of a 45° four-bounce round-trip orbit with $n \approx 1.44$.²

Here, we model the multimode Fano resonances by the interference between light wave that is evanescently coupled with a high-Q mode four-bounce orbit, and coherent light wave that is refractively coupled with a detuned low-Q mode four-bounce orbit. Figure 3 shows the schematic of our Fabry-Perot-like model. Given the focused Gaussian beam comprises an angular distribution of plane waves (with an angular distribution near 2° about θ_c), it is possible that some of the plane wave components are evanescently coupled (Fig. 3 (a)), whereas some of the coherent plane wave components are refractively coupled (Fig. 3 (b)). Figure 3 (a) illustrates ray A evanescently coupled to a four-bounce wavefront-matched orbit having an incident angle θ_A that satisfies the square resonator total internal reflection (TIR) confinement condition $\theta_c < \theta_A < 90^\circ - \theta_c$.² The reflected electric field complex amplitude E_A relative to the incident electric field amplitude E_o can be expressed as follows,³

$$\frac{E_A}{E_o} = r_{FTIR} + \frac{(t_{FTIR})^2 \exp(i\phi_A) \exp(-\alpha L)}{1 - r_{FTIR} \exp(i\phi_A) \exp(-\alpha L)}, \quad (1)$$

where r_{FTIR} and t_{FTIR} are the frustrated TIR reflection and transmission complex coefficients at the air-gap,¹¹ α is the cavity round-trip attenuation, and $L(\theta_A) = 2a \cdot (\sin \theta_A + \cos \theta_A)$ is the four-bounce wavefront-matched round-trip path length.² The phase angle ϕ_A is the phase change due to the wavefront-matched round-trip path length $L(\theta_A)$ and the Fresnel TIR phase shifts at the three sidewalls without coupling to the prism, and thus $\phi_A = n \cdot k \cdot L(\theta_A) + \gamma_R$, where $k = 2\pi/\lambda$ and $\gamma_R = \gamma(\theta_A) + 2 \cdot \gamma(90^\circ - \theta_A)$. At resonances, $\phi_A + \arg(r_{FTIR}) = m \cdot 2\pi$, where m is an integer and $\arg(r_{FTIR})$ is the phase shift due to FTIR. The attenuation α represents cavity loss due to surface wave leakage, scattering loss, and coupling loss at the finite-length coupling interface.

Figure 3 (b) illustrates ray B refractively coupled to a four-bounce wavefront-matched round-trip orbit having an incident angle $\theta_B < \theta_c$. Refractive leakage also occurs at the resonator sidewall opposite to the input-coupled sidewall. The reflected electric field complex amplitude E_B relative to E_o can be expressed as follows,

$$\frac{E_B}{E_o} = r_{FP} + \frac{(t_{FP})^2 r_{ma} \exp(i\phi_B) \exp(-\alpha' L)}{1 - r_{FP} r_{ma} \exp(i\phi_B) \exp(-\alpha' L)}, \quad (2)$$

where r_{FP} and t_{FP} are the Fabry-Perot reflection and transmission complex coefficients at the air-gap,¹¹ r_{ma} (and t_{ma}) are the Fresnel reflection (and transmission) coefficients at the dielectric medium-to-air interface, and α' is the cavity round-trip attenuation. The phase angle $\phi_B = n \cdot k \cdot L(\theta_B) + 2\gamma(90^\circ - \theta_B)$ is the phase change due to the wavefront-matched round-trip path length $L(\theta_B)$ and the Fresnel TIR phase shifts at incident angle $(90^\circ - \theta_B) > \theta_c$ at the two cavity sidewalls orthogonal to the input-coupled sidewall. At resonances, $\phi_B + \arg(r_{FP}) = m' 2\pi$, where m' is an integer and $\arg(r_{FP})$ is the phase shift due to the Fabry-Perot reflection.

The coherent fields E_A and E_B can spatially overlap in the far-field and interfere. The far-field multiple-beam interference intensity I (normalized to the incident intensity I_0) is given as follows,

$$\frac{I}{I_0} = \left| \frac{E_A}{E_o} \right|^2 + f^2 \left| \frac{E_B}{E_o} \right|^2 + 2f \left| \frac{E_A}{E_o} \right| \left| \frac{E_B}{E_o} \right| \cos(\Phi_A - \Phi_B), \quad (3)$$

where f is the angle-dependent amplitude ratio and $(\Phi_A - \Phi_B)$ is the angle-dependent relative phase between spatially extended fields E_A and E_B at the far-field. We assume f is a constant within a sub-degree angle range. At resonance wavelength λ_A that satisfies the resonance condition for orbit A, the interference represents a resonance mode field E_A interferes with an off-resonance

field E_B . The relative phase ($\Phi_A - \Phi_B$) then determines the asymmetric resonance lineshapes.

Figures 4 (a) - 4 (e) show the calculated multimode asymmetric resonance lineshape evolution using (1) – (3) with $|\Phi_A - \Phi_B|$ varies from 0 to 1.1π . We chose $a = 210\text{ }\mu\text{m}$, $n_m = 1.44$, $\theta_A = 44^\circ$, $\theta_B = 42.7^\circ$, $g = 2,000\text{ nm}$, $\alpha = \alpha' = 2\text{ cm}^{-1}$, and $f = 1$. We find good qualitative agreement between the modeled multimode asymmetric resonance lineshapes evolution and the measured spectra (Figs. 2 (a) – 2 (e)).

In conclusion, we experimentally demonstrated Fano resonances in a multimode square micropillar resonator using angle-resolved prism-coupling technique. We observed Fano-resonance-like interference between light waves coherently coupled to a high-Q mode as a resonance and to a low-Q mode as a background. The multimode asymmetric resonance lineshapes evolved over an approximately π phase within a 0.5° range of reflection angles. In contrast to our previous work on single Fano resonances based on the same physical system,³ this Letter highlights the mechanism of multimode Fano resonances due to interference between coherent ray-orbits in multimode cavities. Such multimode Fano resonances should be relevant to wavelength agile devices employing multimode optical cavities.

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Figure Captions

Figure 1. Schematic of the experimental setup. Inset shows two coherently prism-coupled four-bounce ray orbits of a square μ -pillar resonator. n_a : air refractive index, n_m : dielectric medium refractive index, HWP: half waveplate, Pol.: polarizer, MM fiber: multimode fiber, Z: MM fiber scanning direction.

Figure 2. Measured multimode asymmetric resonance lineshapes of $\theta \approx$ (a) 43.98° , (b) 43.84° , (c) 43.80° , (d) 43.68° , and (e) 43.48° . Int.: intensity.

Figure 3 (a) Schematic of an evanescently coupled four-bounce ray orbit in a square micropillar resonator. The dashed line represents the wavefront-matching upon a round trip. The dashed arrow represents the surface wave leakage along the resonator sidewall. (b) Schematic of a refractively coupled four-bounce ray orbit in a square micropillar resonator.

Figure 4. Modeled multimode asymmetric resonance lineshapes. (a) $|\square_A - \square_B| = 0$, (b) $|\square_A - \square_B| = 0.5\square$, (c) $|\square_A - \square_B| = 0.7\square$, (d) $|\square_A - \square_B| = \square$, and (e) $|\square_A - \square_B| = 1.1\square$

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