Fano resonances in prism-coupled square micropillars

Ho-Tong Lee and Andrew W. Poon

Department of Electrical and Electronic Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong SAR, China

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We report Fano resonances in the frustrated total internal reflection (TIR) spectra of a prism-coupled square micropillar. Our angle-selective frustrated TIR technique reveals characteristically asymmetric resonance line shapes, which evolve spectrally over approximately a 2π phase change in the far field within a subdegree range of reflection angles. We theoretically model the asymmetric line shapes by the interference between a high-Q resonance that is evanescently coupled and partially confined by TIR, and a coherent background that is total internally reflected at the prism surface without coupling to the micropillar. © 2004 Optical Society of America

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Optical resonances circulating in dielectric micropillar (μ-pillar) cavities in the form of circular disks, rings, and squares have attracted considerable interest for wavelength-division multiplexing channel add-drop applications. It is well known that a light wave can be partially confined by total internal reflection (TIR) at the μ-pillar sidewalls. When the μ-pillar is input side coupled by either a dielectric coupler or a Gaussian beam, optical resonances are excited when the cavity round-trip wave is wave-front matched with the input coupled wave. The excited modes, without interfering with a coherent background, are generally considered to have a symmetric Lorentzian line shape. However, recent theoretical and numerical investigations revealed pronounced asymmetric resonance line shapes in waveguide-coupled optical microresonators. Such characteristically asymmetric line shapes, known as Fano resonances, result from the interference between a single resonance and a continuum of background modes. Recently, Fano resonances have also been found in two-dimensional nonlinear photonic crystal slabs.

In this Letter we report, for the first time to our knowledge, Fano resonances in frustrated TIR spectra of a prism-coupled square μ-pillar. Our angle-selective frustrated TIR technique reveals characteristically asymmetric line shapes that evolve spectrally over an approximately 2π phase change in the far field within a subdegree range of reflection angles. We theoretically model the asymmetric line shapes by the interference between a high-Q resonance that is evanescently coupled and partially confined by TIR, and a coherent background that is total internally reflected at the prism surface without coupling to the μ-pillar.

Figure 1(a) shows a schematic of the experimental setup. A commercially available μ-pillar with rounded corners in the form of an optical fiber was evanescently coupled with a hemicylindrical UV-grade fused-silica bulk prism. The μ-pillar was positioned perpendicular to the plane of incidence and near the hemicylindrical prism center. To maintain a fixed air gap separation between the μ-pillar and the prism we coated the μ-pillar with two stripes of 0.1-μm-thick gold spacers (to set the minimum gap separation) that were 1 cm apart and glued onto the prism. A Gaussian beam from a wavelength-tunable diode laser at a 1550-nm wavelength (with a laser linewidth of ~300 kHz) was focused with an f/25 cylinder lens onto the prism (with cone angle ~2.3° and spot size ~50 μm) at an incident angle θ = 45° ± 0.5°, where θ is near TIR critical angle θc ~ 44° for refractive-index contrast n = 1.44. Such values of θ favor input coupling to the four-bounce ray orbits in square μ-pillars, as shown in Fig. 1(a). The focused line beam illuminated only the μ-pillar between the spacers. The laser was 45° linearly polarized to measure either the TM- (E-field || the μ-pillar axis) or the TE- (E-field ⊥ the μ-pillar axis) polarized mode. TM measurement is emphasized in the following discussion. The reflected light after coupling to the μ-pillar was collimated by an f/25 cylinder lens at ~90° relative to the laser beam and selectively collected with a 62.5-μm-core multimode fiber at the far field after an analyzer. The multimode fiber was mounted upon a translation stage to facilitate angle-selective reflection measurement along the Z axis (with an angle resolution of ~0.03°) while the prism–pillar coupling remained fixed. The light transmitted tangentially to the μ-pillar sidewall was imaged with an objective lens onto another multimode fiber after an analyzer and was monitored with a near-IR CCD camera. Both the reflected and the

Fig. 1. (a) Schematic of the experimental setup for measuring Fano resonances in a prism-coupled square μ-pillar: MM1, MM2, multimode fibers; PD1, PD2, photodiodes; P, polarizer; A, analyzer. Z, translation. (b) Measured sidewall-transmitted spectrum, (c) measured reflected spectrum at θ = 45°; FSR, free spectral range.
transmitted spectra were lock-in detected with similar photodiodes. The spectral resolution was =0.03 nm, which was limited by our data-taking rate.

Figures 1(b) and 1(c) show the simultaneously measured TM-polarized sidewall-transmitted and -reflected spectrum of the prism-coupled square μ-pillar. The free spectral range of both the reflected (θ = 45°) and the transmitted spectrum is =2.86 nm, consistent with the calculated free spectral range of wave-front-matched four-bounce modes. Only one set of modes is preferentially coupled. The reflected spectrum [Fig. 1(c)] reveals approximately symmetric dips with a maximum Q exceeding 10^4, whereas the transmitted spectrum [Fig. 1(b)] shows approximately symmetric peaks with a higher Q (=2 x 10^4). We attribute the difference in Q to the fact that the reflected and transmitted spectra can originate from different heights along the illuminated μ-pillar, which can have a nonuniform surface roughness or nonuniform gap spacing. Figure 1(c) shows a coupling efficiency that exceeds 50%, which can be improved by narrowing the air gap separation between the prism and the μ-pillar. The ripplelike modulation in Fig. 1(c) is due to residual Fabry–Perot interference in the external-cavity diode laser.

Figure 2 shows the measured TM-polarized angle-selective spectra at reflection angles from θ = 44.94° to θ = 45.71°. Characteristically asymmetric line shapes (Fano line shapes) can be clearly discerned in Figs. 2(b) and 2(d). The Fano line shapes evolve continually over an approximately 2π phase change. The Q value measured in Fig. 2(a) exceeds 5000, and the coupling efficiency exceeds 68%. We observed that the Fano line-shape evolution repeats for another approximately 2π-phase change from θ = 44.45° to θ = 44.94° (not shown here).

Figure 3 is a schematic of our theoretical model. We consider the far-field interference between ray R, which is evanescently coupled to a high-Q square cavity four-bounce mode, and ray B, which is a coherent background that is due to TIR at the prism surface without coupling to the μ-pillar. The interference between two resonance and the coherent background is analogous to the interference between a single resonance and a continuum of background modes according to the theory of Fano resonances. The square cavity has plane-to-plane distance a and a refractive index n_m that is the same as that of the prism. The cavity is separated from the prism with air gap spacing x and refractive index n_a = 1. Ray R is evanescently input coupled to the square cavity at θ = θ_R, which satisfies the square cavity TIR confinement condition θ_c < θ_R < (90° − θ_c). We express the resultant reflected electric field amplitude E_R (normalized to incident field amplitude E_0) as follows:

\[ \frac{E_R}{E_0} = r_{\text{FTIR}} \frac{(t_{\text{FTIR}})^2 \exp(i \phi) \exp(-\alpha)}{1 - r_{\text{FTIR}} \exp(i \phi) \exp(-\alpha)} = \left| \frac{E_R}{E_0} \right| \exp(i \Phi_R), \]  

where \( r_{\text{FTIR}} \) and \( t_{\text{FTIR}} \) are the frustrated TIR complex reflection and transmission coefficients between semi-infinite dielectric media separated by an air gap, φ is the cavity round-trip phase shift, α is the cavity round-trip loss, and Φ_R is the phase of \( E_R \) relative to \( E_0 \) at the far field. We adopt a = -π/2 phase difference between \( r_{\text{FTIR}} \) and \( t_{\text{FTIR}} \). The wavelength-dependent value of φ is given as \( \phi(\lambda) = (2 \pi n L / \lambda) + \gamma_{\text{FTIR}} \), where \( L = 2a(\cos \theta + \sin \theta) \) is the wave-front-matched round-trip length and \( \gamma_{\text{FTIR}} \) is the TIR phase shift at the four cavity sidewalls.

Ray B represents the coherent background that is due to TIR at the prism surface without coupling to the μ-pillar. Such coherent background can be attributed to the fact that part of the laser beam may not spatially overlap the prism–pillar coupling region, as shown in Fig. 2.

\[ \text{Fig. 2. Measured Fano resonances in TM-polarized reflection spectra (a) } \theta = 45.71°, \text{ (b) } \theta = 45.49°, \text{ (c) } \theta = 45.27°, \text{ (d) } \theta = 45.11°, \text{ (e) } \theta = 44.94°. \text{ Int., intensity.} \]  

\[ \text{Fig. 3. Schematic of the theoretical model. Ray R is coupled to a four-bounce ray orbit. Ray B represents a coherent background that is total internally reflected at the prism surface without coupling to the cavity. The dashed arrow represents the surface wave leakage.} \]
The coupling efficiency of $H_{33360}$ can be total internally reflected with part of the laser beam illuminating the prism – see Fig. 3. Moreover, it is conceivable that the high-Q resonances and the coherent background can spatially interfere in the far field and thus display Fano resonances.

In conclusion, we have experimentally demonstrated Fano resonances by using angle-selective prism coupling to the high-Q optical resonances of a square $\mu$-pillar. Our frustrated TIR spectra revealed asymmetric line shapes, which evolve spectrally over a 2$\pi$ phase in the far field within a subdegree range of angles. We theoretically modeled the measured Fano resonances by the interference between a high-Q resonance that is evanescently coupled and partially TIR confined, and a coherent background that is due to TIR at the prism surface without coupling to the $\mu$-pillar. We found good agreement between the measured and the calculated characteristically asymmetric line shapes. Fano resonances in microresonators should be of particular interest in relation to integrated optical switches and filters, for which the optical resonance line shapes can be tuned by application of a relative phase between the high-Q resonances and the coherent background.

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