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Fano resonances in metallic grating coupled whispering gallery mode resonator

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We experimentally demonstrate robust coupling of a metallic grating to the whispering gallery mode (WGM) of a microsphere resonator. The metallic grating coupled resonator forms a hybrid system that generates Fano resonances. Through theoretical modeling and experimental demonstration, we analyze this vertically coupled Fano-WGM structure. It is found that the Fano resonances originate from the interaction between the high-Q WGM and direct reflection of the grating. The Fano resonance shape is found to depend on the polarization state of the incident wave. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4823531>]

Whispering gallery modes (WGMs) represent one type of optical resonances that possess extremely high Q-factors. Exploiting the high Q-factors, WGMs could easily interact with other coherent optical sources to produce Fano resonant features.¹ Studies of WGMs in different microresonator structures have already led to myriads of applications in sensing,² filtering,³ switching,⁴ nonlinear optics,⁵ and quantum electrodynamics.⁶ Amongst these microresonator structures, Fan *et al.* pointed out in theories⁷ and then Liang *et al.* demonstrated in experiments⁸ that a side-coupled waveguide-WGM system could generate sharp asymmetric line-shapes in its transmission spectra. Later, Li *et al.* demonstrated similar Fano features in microtoroid structures by manipulating interactions between two WGMs in one resonator and between two WGMs in two separate resonators, respectively.^{9,10} In a recent work, Hu *et al.* even exhibited Fano resonant features in a system where two coherent optical beams interfere with each other inside single ring cavity.¹¹

However, till now, all the Fano resonances related to WGMs are demonstrated in the so-called side-coupling configurations. High-Q WGM resonators are typically coupled to optical fiber taper in transverse directions. Such coupling method is usually fragile and unstable.^{8–10} Although more robust waveguide-WGM coupling can be implemented in planar waveguide chips, like silicon-on-insulator wafers, the WGM resonators in planar waveguides have much lower Q-factors because of serious sidewall roughness.¹¹ Lack of a robust and efficient coupling method, therefore, becomes the main obstruction for further expanding applications of high-Q Fano resonances. In this letter, by inserting metallic diffractive gratings between feeding waveguides and WGM resonators, we study the Fano resonances in a vertical-coupling configuration. It is found that the Fano resonant features are the consequences of the interactions of the WGMs and the direct reflections. The reflection spectra come in different shapes in correspondence with different incident

polarizations. Our theoretical modeling reveals that the variation in the line-shapes of the Fano resonance originates from the different phases in the directly reflected waves from the metallic grating. This effect could be exploited in ultra-sensitive detection.

The WGM cavity used in this experiment is a silica microsphere formed by melting the end of a single mode fiber,¹² and the microsphere has a diameter of $L = 182 \mu\text{m}$. We use gold grating patterned at the end-face of a single mode fiber (SMF) as the input coupler. The fiber coupler is mounted close to and aimed normally (incident angle $= 0^\circ$) at the WGM microsphere [Fig. 1(a)], namely, vertical coupling. The grating is fabricated by patterning an array of rectangular slits on a 100-nm-thick-gold film that is previously sputtered on the end face of the SMF. The pitch size of the grating is measured to be $\Lambda = 1.1 \mu\text{m}$, and the filling factor is 50/50. The grating is designed as such to phase match its first diffraction orders with the fundamental WGM in the microsphere.¹³ Hence, the diffracted light is able to couple to the WGM in the microsphere, resulting in dips in the reflection spectra.^{13,14}

Fano resonances are observed in the reflection spectra shown in Fig. 2. The gap between the grating and the microsphere decreases continuously. In Fig. 2(a), the Q-factor is measured to be on the order of 10^6 , while the peak-to-dip intensity difference as 19.5% of the background reflection. As the air gap decreases [Fig. 2(b)], the Q-factor maintains on the order of 10^6 , while the peak-to-dip intensity difference increases to 55% of the background reflection. When the air gap further decreases [Fig. 2(c)] and the coupling strength between grating and microsphere becomes stronger, the peak-to-dip intensity difference increases to 73% of the background reflection; on the contrary, the Q-factor sacrificially decreases to the order of 10^4 . Note that the Q-factor measurement has reached our spectral resolution limit (1 pm) for the cases (a) and (b). The resonances should have higher Q's than what are measured in our setup.

In order to understand the formation of Fano resonances in a complex coupling system, transfer matrix method

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FIG. 1. (a) Schematic illustration of the experimental setup for metallic grating coupled WGM microsphere; the insets show the SEM images of fabricated gold grating on the end-face of a SMF. (b) A schematic diagram of the formulated transfer matrices; T_g and T_r stand for the transfer matrix of the grating and coupled WGM resonator, respectively; the fourth layer is the free space beyond the resonator.

(TMM) is applied in our vertically coupled WGM resonator.⁷ Similar to the Fano resonances excited in photonic crystal slabs investigated by Fan *et al.*,¹⁵ the Fano resonances in our grating coupled resonators are results of two interfering pathways: the direct reflection from the grating and the emission from the WGM resonator. The model is formulated as the schematic shown in Fig. 1(b), and the matrix formulation is expressed as

$$\begin{bmatrix} A_4 \\ 0 \end{bmatrix} = T_{total} \begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = T_r T_g \begin{bmatrix} A_1 \\ B_1 \end{bmatrix}. \quad (1)$$

In Eq. (1), A_4 stands for the amplitude of the outgoing field at the fourth layer and A_1 and B_1 are the incident and the reflected field amplitudes in the first layer (SMF), respectively. The air gap between the WGM resonator and the grating is not taken into consideration since the gap size (around 100 nm) is much smaller than the incident wavelength. The overall transfer matrix is thus the product of two essential matrices that correspond to the metal grating (T_g) and the WGM resonator (T_r), respectively.

For the metallic grating, the transfer matrix can be expressed by Eq. (2), where t_g and r_g are the direct reflection and transmission coefficients with the WGM resonator being removed

$$T_g = \begin{bmatrix} \frac{1}{t_g} & -\frac{r_g^*}{t_g} \\ -\frac{r_g}{t_g} & \frac{1}{t_g} \end{bmatrix}. \quad (2)$$

Under TE-polarization (the direction of which is defined as along the length of the gold strips), surface plasmon resonance (SPR) is not excited, and the reflection and transmission from this metal grating can be counted by two contributions: one from the SMF/air interface segment and the other from the SMF/gold film/air interface segment. Considering the filling factor of the grating (50/50), both contributions occupy a proportion of 50%. We calculate the reflection and transmission coefficients using the formulae of Yeh *et al.*¹⁶ For the SMF/gold film/air segment, the metal grating is regarded as one homogeneous layer of gold, while for the SMF/air segment, the metal film is replaced by a homogeneous layer of air. The reflection and transmission coefficients under TE-polarization are thus expressed by

$$r_{d,TE} = 0.5 \cdot \frac{(k_{z1}k_{z2} - k_{z2}k_{z3'})\cos(k_{z2}h) + i(k_{z1}k_{z3'} - k_{z2}^2)\sin(k_{z2}h)}{(k_{z1}k_{z2} + k_{z2}k_{z3'})\cos(k_{z2}h) + i(k_{z1}k_{z3'} + k_{z2}^2)\sin(k_{z2}h)} + (1 - 0.5) \cdot \frac{k_{z1} - k_{z3'}}{k_{z1} + k_{z3'}}, \quad (3a)$$

$$t_{d,TE} = 0.5 \cdot \frac{2k_{z1}k_{z2}}{(k_{z1}k_{z2} + k_{z2}k_{z3'})\cos(k_{z2}h) + i(k_{z1}k_{z3'} + k_{z2}^2)\sin(k_{z2}h)} + (1 - 0.5) \cdot \frac{2k_{z1}}{k_{z1} + k_{z3'}} e^{-ik_{z3'}h}. \quad (3b)$$

In Eq. (3), h is the thickness of the metallic grating; k_{z1} , k_{z2} , and $k_{z3'}$ represent the z-components of the wave vectors in SMF, gold film, and air, respectively (the symbol $3'$ suggests the absence of the silica resonator). Each wave vector is calculated from the equation $k_{zi} = \sqrt{\varepsilon_i k_0^2 - k_x^2}$ ($i = 1, 2, 3$), where ε_i is the permittivity of the i th layer. Since we are considering the field in the zero diffraction direction, k_x vanishes, and k_{zi} is solely determined by the refractive index of the material.

On the other hand, when the incident light becomes TM-polarized (which is defined in the x-direction shown in Fig. 1(b)), SPR is excited in the gold strips. Besides the

contributions from the SMF/gold film/air and the SMF/air interfaces, the SPR in gold strips constitutes the third component of the reflected and transmitted fields, whose phase and amplitude are therefore altered. As to this SPR field component, a simple formula can express its phase (θ) and amplitude (A) according to the Q-factor and the resonant wavelength.¹⁷ For the gold strips used in our experiments, finite-difference time-domain (FDTD) simulations yield the Q-factor of 1.25 and the resonant wavelength of $1.8 \mu\text{m}$, respectively. The operating wavelength ($1.55 \mu\text{m}$) is close enough to the SPR resonant

wavelength under such low-Q-factor circumstance, and the additional phase shift due to the appearance of the SPR is relatively constant over our observation spectral

range. The reflection and transmission coefficients of the gold grating under TM-polarization are expressed as Eqs. (4a) and (4b)

$$r_{d,TM} = 0.5 \cdot \frac{(k_{z1}k_{z2} - k_{z2}k_{z3'})\cos(k_{z2}h) + i(k_{z1}k_{z3'} - k_{z2}^2)\sin(k_{z2}h)}{(k_{z1}k_{z2} + k_{z2}k_{z3'})\cos(k_{z2}h) + i(k_{z1}k_{z3'} + k_{z2}^2)\sin(k_{z2}h)} + (1 - 0.5) \cdot \frac{k_{z3'} - k_{z1}}{k_{z1} + k_{z3'}} + Ae^{i\theta}, \quad (4a)$$

$$t_{d,TM} = t_{d,TE} + Ae^{i\theta}. \quad (4b)$$

For the WGM resonator, the 3rd layer in Fig. 1(b), the transfer matrix considers the effect of both WGM coupling and a Fabry-Perot cavity. The matrix that is associated with WGM coupling can be derived from the results of Xu *et al.*¹⁸ Details regarding coupling efficiencies and gap-size-dependences are not included in the model, because they do not affect the main features of Fano resonances^{7,8,15,18}. The matrix that is associated with Fabry-Perot cavity is constituted of a reflecting interface matrix and a propagation matrix. The Fabry-Perot cavity is confined between the gold grating and the right edge of the resonator [Fig. 1(b)]. Since the light coupled back to the grating through this passage way is very small as compared to the direct reflection and WGM-coupling paths, the Fabry-Perot modes have little influences on the shaping of Fano resonance. The transfer matrix for the resonator layer is expressed in Eq. (5), where we adopt the notations of Fan *et al.*⁷ and use γ to represent the line-width of WGM resonance, ω_0 as the WGM resonant frequency, r as the amplitude reflectivity of the resonator reflecting surface, and $\varphi = k_{z3}L$ as the phase change of light

after traversing one diameter length across the Fabry-Perot cavity

$$T_r = T_{r,FP}T_{r,WGM} = \frac{1}{i\sqrt{1-r^2}} \begin{bmatrix} -1 & -r \\ r & 1 \end{bmatrix} \begin{bmatrix} e^{i\varphi} & 0 \\ 0 & e^{-i\varphi} \end{bmatrix} \times \begin{bmatrix} \frac{(\omega - \omega_0) - i\gamma}{(\omega - \omega_0)} & \frac{-i\gamma}{(\omega - \omega_0)} \\ \frac{i\gamma}{(\omega - \omega_0)} & \frac{(\omega - \omega_0) + i\gamma}{(\omega - \omega_0)} \end{bmatrix}. \quad (5)$$

By summarizing Eqs. (1), (2), and (5), the overall amplitude reflectivity can be calculated. We take the line-width of WGM resonance as $\gamma = 0.002(2\pi c)$ MHz, which is $\Delta\lambda \approx 4.8$ nm at a resonant wavelength of $\lambda_0 = 1.55 \mu\text{m}$, for a rather low-Q resonance to demonstrate details of the shape. To simulate the experimental conditions, we assume the thickness of the grating as $h = 100$ nm, the resonator diameter as $L = 182 \mu\text{m}$, and the amplitude reflectivity of the resonator reflecting interface as $r = 0.02$; using results of Eqs. (3) and (4), we obtain the reflection intensity spectra for both TE- and TM-polarizations, which are shown in Figs. 3(a) and 3(b), respectively. It is observed that the asymmetric line-shape of the Fano resonance goes from a peak to a dip for the TE-polarization (peak-dip resonance), while it reverses its sequence for the TM-polarization by going from a dip to a peak (dip-peak resonance). Small sinusoidal fluctuations are observed on the broad background, and they correspond to the phase changes of the Fabry-Perot modes along the resonator diameter.

The same polarization-dependence is observed in the Fano resonances of experimental and simulation results. FDTD method is used to simulate the reflection spectrum of a gold grating coupled resonator under different incident polarizations. Due to limitations of the computing power, a small silica micro-disk resonator with a diameter of $L = 16 \mu\text{m}$ is calculated. As shown in the graphs presented in Figure 4, it is found that despite a striking size difference between the resonator used in simulation and in experiment, the TE-polarization is always associated with peak-dip resonances while TM-polarization with dip-peak resonances. In relation to the results derived from transfer matrix method, Figs. 4(a) and 4(c) correspond to that of Fig. 3(b) while Figs. 4(b) and 4(d) correspond to that of Fig. 3(a). The phase difference between TE and TM-polarization determines the on-off or off-on sequence of the Fano resonances, regardless of resonator size, coupling strength, input frequency, or grating geometry.

FIG. 2. Reflection spectra of the grating coupled microsphere when the air gap between the resonator and grating coupler is (a) 175 nm; (b) 105 nm; (c) 35 nm. The incident wave is transverse electric (TE) polarized.

FIG. 3. Theoretical reflection spectra of the grating coupled resonator for (a) TE-polarization, (b) TM-polarization. The resonance wavelength is $1.55\ \mu\text{m}$, resonant line-width is around $4.8\ \text{nm}$, $\Lambda = 1.1\ \mu\text{m}$, $h = 100\ \text{nm}$, $L = 182\ \mu\text{m}$. Coupling efficiencies for TE and TM-polarized modes are assumed to be 100%.

FIG. 4. Simulated reflection spectrum for a silica microdisk with a diameter of $16\ \mu\text{m}$ and grating pitch size of $1.2\ \mu\text{m}$ when incident light is (a) TM-polarized, (b) TE-polarized, experimentally measured reflection spectrum for a silica microsphere with a diameter of $182\ \mu\text{m}$ and a gold grating pitch size of $1.1\ \mu\text{m}$ when incident light is (c) TM-polarized; (d) TE-polarized, both fundamental and higher order WGMs are observed; the insets show zoom-in views of the Fano resonances.

In conclusion, we have demonstrated a metallic grating coupled WGM microsphere and theoretically analyzed the vertical-coupling system. The gold grating patterned at the end-face of a single mode fiber is both efficient and robust in coupling to the high-Q WGM resonators. With the current coupler and resonator, a Q-factor of at least 10^6 is achieved; an on-off intensity difference of at least 73% of the reflection background is observed. On the other hand, an additional phase shift attributed to the direct reflection from grating is found to be able to flip the Fano resonance, demonstrating two different Fano shapes corresponding to TE- and TM-polarizations. With such metallic grating coupled whispering gallery mode resonator, sensing, switching, filtering as well as nonlinear optical devices that rely on high-Q WGM resonators would become practically feasible.

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