<table>
<thead>
<tr>
<th><strong>Title</strong></th>
<th>Fano resonances in metallic grating coupled whispering gallery mode resonator</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Author(s)</strong></td>
<td>Zhou, Yanyan; Zhu, Di; Yu, Xia; Ding, Wei; Luan, Feng</td>
</tr>
<tr>
<td><strong>Citation</strong></td>
<td>Zhou, Y., Zhu, D., Yu, X., Ding, W., &amp; Luan, F. (2013). Fano resonances in metallic grating coupled whispering gallery mode resonator. Applied physics letters, 103(15), 151108-.</td>
</tr>
<tr>
<td><strong>Date</strong></td>
<td>2013</td>
</tr>
<tr>
<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/10220/18387">http://hdl.handle.net/10220/18387</a></td>
</tr>
<tr>
<td><strong>Rights</strong></td>
<td>© 2013 AIP Publishing LLC. This paper was published in Applied Physics Letters and is made available as an electronic reprint (preprint) with permission of AIP Publishing LLC. The paper can be found at the following official DOI: [<a href="http://dx.doi.org/10.1063/1.4823531">http://dx.doi.org/10.1063/1.4823531</a>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.</td>
</tr>
</tbody>
</table>
Fano resonances in metallic grating coupled whispering gallery mode resonator
Yanyan Zhou, Di Zhu, Xia Yu, Wei Ding, and Feng Luan

Citation: Applied Physics Letters 103, 151108 (2013); doi: 10.1063/1.4823531
View online: http://dx.doi.org/10.1063/1.4823531
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/103/15?ver=pdfcov
Published by the AIP Publishing
Fano resonances in metallic grating coupled whispering gallery mode resonator

Yanyan Zhou,1,2 Di Zhu,1,2 Xia Yu,2 Wei Ding,3 and Feng Luan1,4,a)  
1School of Electrical and Electronic Engineering, Nanyang Technological University, Block S2,  
50 Nanyang Avenue, Singapore 639798  
2Precision Measurements Group, Singapore Institute of Manufacturing Technology, 71 Nanyang Drive,  
Singapore 638075  
3Key Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China  
4OPTIMUS Nanyang Technological University, Singapore 639798

(Received 5 July 2013; accepted 12 September 2013; published online 8 October 2013)

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 myriad of applications in sensing,2 filtering,3 switching,4 nonlinear optics,5 and quantum electrodynamics.6 Amongst these microresonator structures, Fan et al.7 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.9 demonstrated similar Fano features in microrod 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 ultrasensitive 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 μm. 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°) 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 λ = 1.1 μm, 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 106, while the peak-to-dip intensity difference is 19.5% of the background reflection. As the air gap decreases [Fig. 2(b)], the Q-factor maintains on the order of 105, 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 104. 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

a)Electronic mail: luanfeng@ntu.edu.sg
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. Similar to the Fano resonances excited in photonic crystal slabs investigated by Fan et al., 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

$$
\begin{align*}
\begin{bmatrix} A_4 \\
0 
\end{bmatrix} = T_{total} \begin{bmatrix} A_1 \\
B_1 
\end{bmatrix} = T_r T_g \begin{bmatrix} A_1 \\
B_1 
\end{bmatrix}.
\end{align*}
$$

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

$$
T_g = \begin{bmatrix} 1 & -r_g^* \\
-r_g & 1 
\end{bmatrix}.
$$

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. 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

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

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

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 $k_{z3} = \sqrt{\varepsilon_i k_0^2 - k_{z2}^2}$ ($i = 1,2,3$), where $\varepsilon_i$ is the permittivity of the $i$th layer. Since we are considering the field in the zero diffraction direction, $k_{z1}$ vanishes, and $k_{z2}$ 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 ($\theta$) and amplitude ($A$) according to the Q-factor and the resonant wavelength. 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 $\mu$m, respectively. The operating wavelength (1.55 $\mu$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)

\[ r_{d,TM} = 0.5 \cdot \frac{(k_z^0 - k_z^1)^2 \cos(k_z^0 h)}{(k_z^0 + k_z^2)^2 \cos(k_z^0 h) + 2i(k_z^0 - k_z^2) \sin(k_z^0 h) + (1 - 0.5) \cdot \frac{k_z^2 - k_z^1}{k_z^1 + k_z^2} + Ae^{i\theta},} \]

\[ t_{d,TM} = t_{d,TE} + Ae^{i\theta}. \] (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. 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. 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. and use \( \gamma \) to represent the line-width of WGM resonance, \( \omega_0 \) as the WGM resonant frequency, \( r \) as the amplitude reflectivity of the resonator reflecting surface, and \( \varphi = k_z L \) as the phase change of light after traversing one diameter length across the Fabry-Perot cavity

\[ T_r = T_{r,FP}T_{r,WGM} = \frac{1}{i\sqrt{1 - r^2}} \begin{bmatrix} -1 & -r \\
-r & 1 \end{bmatrix} \begin{bmatrix} e^{i\varphi} & 0 \\
0 & e^{-i\varphi} \end{bmatrix} \times \begin{bmatrix} (\omega - \omega_0) - i\gamma \\
(\omega - \omega_0) + i\gamma \end{bmatrix} \begin{bmatrix} (\omega - \omega_0) + e^{i\gamma} \\
(\omega - \omega_0) + e^{-i\gamma} \end{bmatrix}. \] (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 \( \Delta \omega \approx 4.8 \text{ nm at a resonant wavelength of } \omega_0 = 1.55 \mu m \), 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 \( h = 100 \mu m \), the resonator diameter as \( L = 182 \mu m \), 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 \( L = 16 \mu m \) 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.

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.
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.

We wish to acknowledge the funding support from SERC Advanced Optics Engineering TSRP Grant 1223600011 and Singapore Ministry of Education Academic Research Fund (MOE2011-T2-2-120).

1. A. E. Miroshnichenko, S. Flach, and Y. S. Kivshar, Rev. Mod. Phys. 82, 2257 (2010).