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Metallic diffraction grating enhanced coupling in whispering gallery resonator

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Abstract: For the first time, metallic diffraction grating is investigated to enable efficient coupling in the whispering gallery resonator (WGR). Six-fold field enhancement in the resonator is achieved with respect to their dielectric counter-parts. This higher coupling efficiency is attributed to the surface plasmon excitation which drives the whispering gallery mode along the grating. Fano resonances have been observed in optical reflection. With the metallic grating, single-port end-fire WGR configuration becomes possible - a scheme that has not been demonstrated in any other WGR coupling devices. Hence, it serves as a prototype for portable whispering gallery devices potentially useful in sensing, switching and nonlinear applications.

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References and links
1. Introduction

Whispering gallery resonator (WGR) has been applied to many fields of applications including lasers [1], optical sensing [2] and filtering [3]. They are especially useful in providing extremely high-Q factors and small mode volume [4]. Traditionally, the excitation of whispering gallery mode (WGM) in a WGR relies on a dielectric coupler: from attenuated total internal reflection off a prism [5], to tapered optical fiber [6] or fiber tip [7], to angle/side polished fiber tip/bend [8,9], and phase grating attached to the end of a fiber [10]. Because it is the precise overlap of the evanescent fields that determine the energy exchange, coupling efficiency to a WGR relies heavily on the relative position of the coupler and resonator. Thus, precise positioning control is crucial to dielectric couplers. Up to now, the tapered fiber provides the highest coupling efficiency [6]. However, due to its fragile and easy-to-contaminate natures, tapered fiber is not a good coupler for integrated photonics applications. On the other hand, the side-polished fiber bends [9] are robust, but this class of WGM couplers is especially difficult to control the phase-match coupling.

Plasmonic effects have been introduced to enhance the coupling of WGM in many works: it has been demonstrated that its high-Q performance can be used to enhance the sensitivity of plasmonic sensing [2]; vice versa, coupling enhancement of WGM by plasmonics is also possible with gold-film assisted prism [11], gold nanorods [12], gold nanowires [13] and metal clad planar waveguide [14], and 2D array of plasmonic nano-focusing structures [15]. However, the existing plasmonic assisted WGM couplers still require considerable effort in positioning to achieve critical coupling; the loss associated with metallic structure on the WGR always reduces the high-Q performance of the resonator; and the coupling scheme that utilizes nanowire/nanoparticles limit the coupling to a fixed resonance of the plasmonic structure itself.

In this work, we propose to use a metallic grating to serve as a WGM coupler. Because of the unique scattering features of metallic periodic structure, more power can be coupled into a WGM cavity comparing with a dielectric grating coupler. Moreover, strong reflection signal can be collected so that single-port configuration is possible. The structure investigated is depicted in Fig. 1. The metallic grating consists of rectangular grooves (height h, period a) with a filling factor of 50%. It is situated on a silica substrate (i.e., an optical fiber) and is a distance d away from the bottom of the WGR. The metallic grating scatters the normally incident Gaussian wave into various diffraction orders, which are then coupled to the WGM.
2. Results and discussion

The period of the grating is designed to have its first diffraction order phase-match to the first radial order WGM in a silica micro-disk with a radius of 4 µm and a refractive index of 1.5. For the diffraction grating, the effective refractive index of the diffracted mode can be calculated using the grating equation

\[ n_i \sin \theta_q = n_i \sin \theta_i - q\lambda / a \]

(\(q\) is the diffraction order, \(n_i\) is the effective mode index of the diffraction order, \(\theta_q\) is the diffraction angle of the \(q_{th}\) diffraction order, \(\theta_i\) is the incident angle, \(n_i\) is the refractive index of the incident medium and \(\lambda\) is the incident wavelength). At normal incidence, the grating equation associated with the \(-1\) diffraction mode can be reduced to \(n_{\text{grating}} = \lambda / a\), where \(n_{\text{grating}}\) is the x-component of the effective mode index. In order to satisfy the phase-match conditions, we calculate the effective mode index of the first radial order WGM (\(n_{\text{WGM}}\)) using the equations given in [8] and equate it with the effective mode index of grating, i.e. \(n_{\text{grating}} = n_{\text{WGM}}\). The grating period is then found to be 435 nm for an incident wavelength of 550 nm. We choose this pitch size to couple to the spectral transmission ranging from 500 nm to 600 nm. The height of the grating is fixed at 100 nm and the whole structure is placed in vacuum which has a refractive index of 1. By benchmarking with a dielectric grating WGM coupler [10], we performed the calculations for a silica grating with the same geometry using numerical simulation (Lumerical FDTD Solution).

In the simulation, the incident wave is TM-polarized to excite the surface plasmon resonance (SPR). The TM-polarization is defined to be along the x-axis while TE-polarization in-and-out of the x-y plane. Because of the bending effect of the grating diffraction, the indicated TM-polarization is able to excite TM-polarized WGM in the resonator. In addition, we found that the coupled field strength hardly varies with the Gaussian beam size when the beam is at least 4 grating periods wide. A beam width of 2 µm is used.

Figure 2(a) shows the normalized optical power coupled into the WGM micro-disk by a gold grating and a silica grating, where \(d\) is respectively optimized for maximum coupled field intensity. For the gold grating, normalized intensity distributions for the first and second radial order are also shown by the insets. The distribution images are normalized to their own field maxima. It is observed that the gold grating couples almost 6 times of the power with the silica grating. Figure 2(b) and 2(c) compares the coupled field pattern before any light travels one round trip of the micro-disk. It is observed that the dielectric grating shoots out most of
the light as zero diffraction order (in the y-axis) while the gold grating diverts more light to the curvature of the micro-disk.

To maximize the coupled field intensity in the WGR, critical coupling needs to be achieved. For conventional waveguide-coupled WGM, critical coupling occurs when the round trip loss equals the amount of power coupled from the waveguide into the WGR [16]. Round trip loss is obtained by calculating the cavity ring-down time of the same micro-disk (R = 4 µm, n = 1.5) with a dipole source placed very near to the disk, and the round trip loss is 12.6% for a resonant wavelength of 564.7 nm. The amount of power coupled into the WGR from the waveguide is designated by the coupling coefficient κ, which is defined as

\[ \kappa(\omega) = \frac{\text{Coupled Power}(\omega)}{\text{Source Power}(\omega)} \] [17].

Hence, the κ that yields critical coupling (κc) for the abovementioned micro-disk is 12.6%. However, this κ is calculated for a single mode coupling scenario. For a grating-coupled WGR, the incident light is diffracted into a series of modes, of which only a fraction are coupled to the WGM. Figure 3 shows the coupled field intensity and κ for a range of d at their respective resonant wavelengths. For both cases, the coupling coefficients decrease monotonously with d while the coupled field intensity first increases and then decreases with increasing d. When d is optimized to achieve maximum coupled field intensity, the corresponding coupling coefficients (κmax) for the silica grating and gold grating are both much smaller than the κc calculated for waveguide-coupled WGM (12.6%). This indicates that those modes that can be coupled into the WGR fulfil the critical coupling requirements while all the other modes do not contribute to the coupling. We denote those modes that can be coupled to WGM as the 'useful modes'. When κmax is achieved, the ratio of useful modes over total power can be calculated as

\[ \eta = 2 \times \frac{\kappa_{\text{max}}}{\kappa_c} \]

where the factor 2 is attributed to the fact that light is coupled into the WGR in both clockwise and counterclockwise directions. For the silica grating coupler, only a maximum of 8.9% of the total power can be coupled to WGM; for the gold grating coupler, a maximum of 57% can be coupled, suggesting a 6-fold field enhancement with the metallic grating coupler.

All the above mentioned results are calculated for the case when incident light is TM-polarized. For TE-polarized light, SPR is not excited in the metallic grating and the coupling with silica and gold grating offers almost the same performance. So overall, metallic grating is a better coupler to different polarizations. Especially, the metallic grating is useful for
sensing applications since TM-polarization generally has a higher sensitivity as compared to TE-polarization [18].

Fig. 3. Electric field intensity and coupling coefficient as a function of the separation $d$ for (a) silica grating; (b) gold grating. The intensity is measured at spatial maximum at the respective resonant wavelengths for each data point. The insets show the respective field distribution of the coupled WGM when $d$ is optimized for maximum coupled field intensity (silica: $d = 58$ nm; gold: $d = 133$ nm), both color scale and left axis of the graphs are normalized to the results of gold grating.

Gold is a good reflector in visible to NIR regime as compared to dielectric materials. Reflectivity associated with metallic grating is much larger than its dielectric counterpart. Because of the plasmonic effect, gold grating is more efficient in coupling to the transverse propagating mode, so that the losses due to WGM in the reflection signal is more significant. As Fig. 4(a) shows, the reflected power with a bare silica grating is no more than 0.5% of the launching power. With a WGR placed at $d = 58$ nm from the grating, the reflection signal increases and the oscillations pattern is due to the Fabry-Perot effect of the zero diffraction order. The loss dips attributed to WGM are not clearly observed. In contrast, as Fig. 4(b) shows, the gold grating provides substantially stronger reflection with or without the presence of WGR. The WGM spectrum dips can be distinguished with good visibility and the Fabry-Perot oscillation is weak. Compared with other fiber tip based WGM couplers [8], the gold grating offers the advantage of monitoring the WGM with single port configuration, which is especially useful for sensing applications.

Fig. 4. Reflected optical power spectrum with and without the whispering gallery micro-disk for (a) silica grating ($d = 30$ nm); (b) gold grating ($d = 135$ nm).

To investigate the spectral response of the metallic grating coupler, we changed the period of the gold grating to 1.3 $\mu$m and simulated the coupling to the abovementioned WGR in the NIR range. The coupled power spectrum is shown in Fig. 5(a) and the field distribution for a
wavelength of 1.148 µm is shown in the inset. As the wavelength increases, the free spectral range increases and Qc decreases. The power distribution demonstrates that it is still possible to effectively couple to WGM within the infrared region where surface plasmon resonance (SPR) of nanoparticle/nanowire would be significantly reduced. The reflected optical power spectra are shown in Fig. 5(b). The spectrum where WGR is present demonstrates unique features at the WGM loss dips: for all the WGM dips within the spectral range investigated, it is immediately followed by a power peak, so that the spectrum is consisted of a great number of vertical lines. Such phenomenon results from the interplay of two resonance effects – Wood anomaly and WGM, which are combined to modify the shape of the resonances. The resulted sharp resonance lines are Fano resonance which potentially holds even higher Q-factor [19]. Wood anomaly was first discovered in the metallic grating [20]. The spectral overlap of the high-Q WGM and low-Q Wood anomaly gives rise to even stronger Fano resonance. Fano resonances in the whispering gallery resonator have triggered interesting physics and new applications [21–23]. Different from [21] whereby the Fano resonance is the result of engineering two WGMs in a single resonator, the plasmonic grating coupled WGR is able to control the resonance with at least one more degree of freedom, i.e. with the SPR.

Fig. 5. (a) Normalized optical power spectrum for coupled WGM by a gold grating (d = 310 nm; h = 100 nm; a = 1300 nm), inset: field distribution for the WGM at a resonant wavelength of 1.148 µm, color scale is normalized to the image itself; (b) Reflected optical power spectra of the gold grating with and without the presence of WGR.

3. Conclusion

We proposed, for the first time, the coupling between a whispering gallery resonator and a metallic diffraction grating. Compared to the dielectric grating for TM-polarization, the metallic grating coupler offers 6-fold coupled field enhancement with end-fire coupling scheme. Compared to other fiber tip based WGM couplers, the metallic grating enables single-port configuration by monitoring the reflection signal. By varying the grating period, the metallic grating can be designed to potentially couple to a broad spectral range and to resonators of different sizes and refractive indexes. It can be easily integrated into a compact coupling device, such as an optical fiber, to make WGM-based sensing applications practical. Moreover, the interaction of Wood anomaly and whispering gallery mode resonances in the plasmonic grating-coupled resonator gives rise to Fano resonances, which hold promising potentials for optical switching, sensing, lasing and nonlinear as well as slow-light devices.

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