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Optimal coupling to high-Q whispering gallery modes with a sub-wavelength metallic grating coupler

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ABSTRACT

Gold grating patterned on the end facet of an optical fiber is able to excite whispering gallery mode (WGM) in a silica microsphere. With a direct pathway of the metal reflection, the coupled WGM is able to superimpose and create an asymmetric Fano resonance. Since multiple resonances are present – the WGM, grating reflection, and a weak Fabry-Perot resonance along the diameter of the sphere – it is difficult to evaluate the power efficiency directly from the measured spectrum. Using temporal coupled-mode theory, a general model is constructed for the end-fire coupling from a grating to a WGM resonator.

Keywords: Microresonators, power coupling, diffraction grating, fiber optics

1. INTRODUCTION

Due to ultrahigh quality factor and small modal volume, the whispering gallery mode (WGM) resonators have been widely applied in many fields of linear [1, 2] and nonlinear [3, 4] applications. Traditionally, the excitation of whispering gallery mode (WGM) in a WGR relies on a dielectric coupler: from attenuated total internal reflection of 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]. Efficient coupling to the WGM resonators has long been regarded as the key challenge of the resonator study. For WGM resonator based applications to happen, mechanical stability of the coupling bears equal importance. Up to now, the tapered fiber provides the highest coupling efficiency. However, due to its fragile and easy-to-contaminate natures, tapered fiber is not a suitable coupler for integrated photonics applications. On the other hand, the side-polished fiber bends are robust, but this class of WGM couplers does not allow the precise control of the phase-matching conditions.

In this work, we present a novel WGM coupler based on the metallic diffraction grating. Because of the unique scattering features of the metallic periodic structure, the metallic grating has higher first-order diffraction efficiency as compared to a dielectric grating of the same dimensions. Therefore, the coupling efficiency of a metallic grating to the WGM resonator is expected to be much better than that of the dielectric one. Moreover, strong reflection signal can be collected so that single-port configuration is possible. As the grating is fixated on the end facet of a single mode fiber, both the mechanical strength and durability of use both significant improved. The metallic grating coupled microresonator hence gives rise to all-fiber cavity with single-port coupling configuration.

2. DEMONSTRATION OF COUPLING

The coupling configuration is depicted in Fig.1, where a silica microsphere resonator is aligned vertically above a one-dimensional gold grating patterned on the end facet of a SMF. Tunable laser inputs light at telecommunication wavelength from the SMF to excite WGM in the sphere. Reflection is observed and measured using a fiber based optical circulator. Transmitted light is captured by a free-space photodetector at the exiting end of the sphere. Before passing through the grating, light travels as a single mode, the field amplitude of which is denoted s_+ , where the “+” sign indicates power flow to the resonator. After the grating, the single mode in the fiber is supposedly diffracted to a zeroth-order and two symmetric first-order modes (all the other diffraction orders are negligible). However, since the grating has sub-wavelength pitch size, the diffracted modes are evanescent waves. When the microsphere is placed in the vicinity of the grating, WGM can be coupled to the evanescent waves of the first-order diffractions that bear transverse

wavevectors (along the x-axis). The coupling coefficient of the i^{th} input mode is defined as κ_i . At the exiting end of the sphere, amplitude of the field (s_i) that comes out of the resonator is indicated by the “–” sign.

Fig. 1. Schematic illustration describing the diffraction grating coupled microsphere resonator.

Using the coupling setup of Fig. 1, the reflected spectrum of a microsphere resonator is presented in Fig. 2. The quantum mode numbers of each resonance is verified using the results of Reference [11] and are then labeled in Fig. 2. It is found that higher azimuthal order WGMs are excited due to the eccentricity splitting of the sphere – perfect spherical shape is impossible to fabricate and the resonator always results in a spheroid. Moreover, higher radial-order WGMs also appear.

Fig. 2. Reflection spectrum of a metallic diffraction grating coupled spherical resonator using a silica microsphere with a diameter of around $100\mu\text{m}$. The metallic diffraction grating coupler has a thickness of 100nm and a pitch size of $1.1\mu\text{m}$.

3. MATHEMATICAL MODEL

To understand the power transfer mechanism of the many scattering processes of the structure, a mathematical model is set up to simulate the coupling phenomenon. Fig. 1 tells the existence of two resonating structure: the diffraction grating and the resonator. A cascaded scattering model can hence be set up that investigates the resonances separately. A schematic picture of the model is presented in Fig. 3.

Fig. 3. Schematic illustration of cascaded scattering system of (a) microsphere resonator; and (b) diffraction grating.

There are altogether eight scattering ports in which power exchange can happen between different optical elements. The two resonating structures are the microsphere resonator and diffraction grating which are described in Fig. 3(a) and (b) respectively. Diffraction is characterized by Port 1-4 (Fig. 3(b)), with Port 1 aligning with the SMF, Port 2 and 3 in the directions of transmitted and reflected transverse diffractions (x-axis) respectively, and Port 4 as the transmitted zeroth-order diffraction that cannot be coupled to the WGM. The dissipative loss induced by the metallic material is small as compared to the coupled power, so the grating is considered as lossless. Light interaction with the microsphere resonator happens for Port 5-8, where input of Port 5 and 6 are the output of Port 2 and 4 respectively (indicated by the dotted lines across figures). The WGM resonator system (Fig. 3(a)) can be viewed as two pairs of input-output ports that correspond to the coupled WGM (Port 5 & 7) and the uncoupled background (Port 6 & 8). When the resonator system is cascaded with the diffraction system, a 4-port network is obtained, with the end port numbers labeled as I, II, III, and IV that correspond to Port 1, 3, 7 and 8 respectively. The scattering matrix of this cascaded 4-port network is calculated from the independent scattering matrices of the resonator and grating.

First, the scattering matrix of the diffraction grating is found as in Equation (1).

$$\begin{pmatrix} s_{1-} \\ s_{2-} \\ s_{3-} \\ s_{4-} \end{pmatrix} = \exp(j\phi) \begin{bmatrix} r_{11} & jt_{12} & r_{13} & jt_{14} \\ jt_{12} & r_{22} & jt_{23} & r_{24} \\ r_{13} & jt_{23} & r_{33} & jt_{34} \\ jt_{14} & r_{24} & jt_{34} & r_{44} \end{bmatrix} \begin{pmatrix} s_{1+} \\ s_{2+} \\ s_{3+} \\ s_{4+} \end{pmatrix} \quad (1)$$

where the amplitude scattering coefficient from one port to another is indicated by a pair of port labels in the subscripts: the first label as the input port and the second as the output port. For example, r_{24} is the amplitude response of Port 4 when power of amplitude 1 is input to Port 2; r_{22} is the amplitude reflection coefficient of Port 2. Since the system is lossless and reciprocal, the scattering coefficients remain the same when the input and output ports are exchanged, i.e., we have both the reflection and transmission coefficients satisfying $r_{ik}=r_{ki}$ and $t_{ik}=t_{ki}$, where i and k are any integer number between 1 and 4. The phase change φ is introduced to indicate light propagation through grating that is determined by the grating design.

Second, based on temporal coupled theory, the corresponding scattering matrix for the resonator coupling is obtained as Equation (2).

$$\begin{pmatrix} s_{5-} \\ s_{6-} \\ s_{7-} \\ s_{8-} \end{pmatrix} = \begin{bmatrix} \mp jf & 0 & j - jf & 0 \\ 0 & 0 & 0 & 0 \\ j - jf & 0 & \mp jf & 0 \\ 0 & j & 0 & 0 \end{bmatrix} \begin{pmatrix} s_{5+} \\ s_{6+} \\ s_{7+} \\ s_{8+} \end{pmatrix} \quad (2)$$

where the function $f = 2\sigma_e / [j(\omega - \omega_0) + (\sigma_e + \sigma_0)]$ is used to represent the spectral response of resonance while the reflection coefficient of the resonator is considered as 0 (transmission coefficient is 1). The coefficients σ_0 and σ_e represent the losses due to the resonator and coupling to an external coupler respectively. The resonance frequency is represented by ω_0 . Details of derivation of Equation (2) can be found in Reference [12].

Finally, the overall transmittance and reflectance of the cascaded system are listed below.

$$R_I = \left| r_{11} + \frac{f \cdot t_{12}^2 \exp(j\varphi)}{f \cdot r_{22} \exp(j\varphi) \mp j} \right|^2 \quad (3)$$

$$R_{II} = \left| r_{13} + \frac{f \cdot t_{12} t_{23} \exp(j\varphi)}{f \cdot r_{22} \exp(j\varphi) \mp j} \right|^2 \quad (4)$$

$$T_{III} = \left| \frac{\mp t_{12} (f - 1) j}{f \cdot r_{22} \exp(j\varphi) \mp j} \right|^2 \quad (5)$$

$$T_{IV} = \left| -t_{14} + \frac{f \cdot r_{24} t_{12} \exp(j\varphi)}{f \cdot r_{22} \exp(j\varphi) \mp j} \right|^2 \quad (6)$$

In experiment, only the reflection of Port I is collected while that of Port II is diffracted out of the fiber core and driven into free space. For transmission, since Port III and IV are physically inseparable, responses of both ports are captured by the free space detector. Hence, we have the reflectance $R = R_I$ and the transmittance $T = T_{III} + T_{IV}$.

4. EVALUATION OF EFFICIENCY

In contrary to fiber taper coupled WGM resonance that yields symmetric line-shape, the grating coupled microsphere involves multiple resonances and scattering processes that end up with asymmetric Fano resonances. Coupling efficiency cannot be directly assessed from an asymmetric resonance in the transmitted spectrum. However, it can be roughly evaluated in the case of almost symmetric resonance. When reflection coefficients are small, Equation (5-6) gives $T \approx t_{12}^2 + t_{14}^2$ for $|\omega - \omega_0| \gg 0$ and $T \approx t_{14}^2$ for $\omega = \omega_0$. In this case, the resonance is almost symmetric and the resonance dip

almost coincides with the resonance frequency. Since the reflected power is small, $t_{12}^2 + t_{14}^2$ can be considered as the total power (the background power level in the spectrum). The coupling efficiency (t_{12}^2) can then be calculated by directly evaluating the ratio of resonance depth with the transmission background power.

In the experiment, a grating with small filling factor (<30%) and thin thickness (~60nm) is used to purposely inflict small grating reflection coefficients. The scattering coefficients that appear in Equation (1) are modelled using FDTD method for a lossless grating (made of perfect electrical conductor). The power reflection coefficient r_{11}^2 is evaluated as ~0.03 from the experimental readings. The reflection coefficients r_{22} and r_{24} are both found to be comparable with r_{11} ($r_{22} \approx r_{24} \approx r_{11}$). When the resonator is on-resonance, the transmission coefficients t_{12} is found comparable with t_{14} ($t_{12} \approx t_{14}$). Figure 4 shows the modelled resonance alongside two adjacent WGM resonances coupled in experiment for (at critical coupling). To show clearly the spectral resonance, a large linewidth of $\sigma_0 = 0.26\text{nm}$ is used to obtain the resonance of Fig. 4(b).

Fig. 4. Transmission and reflection spectra of a gold grating coupled microsphere in (a) experiment; (b) theoretical model.

Fig. 4 demonstrates good agreement between the experiment and modelling. From the results of Fig. 4(a), it is verified that the gold grating used in this section of work gives almost symmetric resonance shapes. Hence, the true coupling efficiency of the grating can be evaluated at critical coupling by the depth of the transmitted resonance. as around 51%.

5. CONCLUSION

Despite the lossy nature of metal, the metallic diffraction grating offers improved efficiency over a dielectric grating of the same dimension. Although it has been difficult to assess the coupling efficiency directly from the coupled Fano resonance, theoretical model is set up to assess the power coupling of an almost symmetric transmitted resonance. Quite straightforwardly, the coupling efficiency is expected to increase if more light is bent to the transverse direction in the grating transmission, which can be realized by improving the diffraction efficiency of the first diffraction orders. The metallic diffraction grating makes all-fiber single-port microresonator-based systems possible. It has a promising future in supporting the many applications of WGM resonators.

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