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Enhanced whispering gallery mode sensors

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ABSTRACT

Optical whispering gallery mode (WGM) biochemical sensors operate by tracking changes in resonant frequency as materials enter the evanescent near-field of the resonator. To achieve the smallest limit of detection, it is desirable for WGM sensors to exhibit as large a frequency shift as possible for a material of a given size and refractive index, as well as the ability to track as small a frequency shift as possible. Previously, plasmonic nanoantennas have been coupled to WGM resonators to increase the magnitude of resonance shifts via plasmonic enhancement of the electric field, however this approach also results in increased scattering from the WGM, which degrades its quality factor, making it less sensitive to extremely small frequency shifts. This degradation is caused by the ohmic and scattering dissipation caused by metallic nanoantennas. Using simulations, we show here that the precise positioning of nanoantennas coupled to a microtoroid WGM resonator can be used to overcome this drawback and achieve ultrahigh-Q plasmonic cavity modes simultaneously with electric field enhancement. It is shown that a nanoantenna composed of two similarly coupled nanorods supports higher Q modes than a single nanorod antenna. Our results have immediate application in the context of optical sensing.

Keywords: Microcavity, nanoantenna, plasmonic cavity mode

1. INTRODUCTION

In the last decade, ultrahigh quality factor (Q) microcavities have attracted considerable attention in the context of optical sensing [1-4] and even single molecule detection [5] due to their enhanced light-matter interaction [1,2]. The surface field enhancement of plasmonic nanostructures such as nanorods and nanospheres has also been explored extensively and their potential capability of increasing the sensitivity of traditional sensors has been investigated in many works [8-13]. Here, the central idea is to couple these optical nanoantenna to an optical cavity and as a result enhance the light-matter interaction [9,17]. These plasmonic-photonics systems support so called 'plasmonic cavity modes', which are highly desired for optical sensing application [6, 14, 15]. However, the fundamental limitation here is to overcome unwanted introduced loss to the optical mode, due to the metallic nature of the nanoparticle. A considerable drop in the cavity Q factor of such systems has been reported, for example, from 10^8 for a bare toroid to 10^4 for a toroid with an equally spaced array of several hundred nanoantennas [6]. In this work, we show how the use of rationally designed optical nanoantennas coupled to microtoroids can overcome this limitation of surface plasmons and as a result keep the Q of the system almost intact while maintaining the surface field enhancement of plasmonic cavity modes.

This paper is organized as follows: Section two introduces the system composed of a microtoroid coupled to a nanoantenna, Section three covers the optimization results for a single and two coupled nanorods. Finally, we expound on the basic conclusions obtained from our proposed systems.

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2. PLASMONIC CAVITY MODE

A plasmonic cavity mode is a result of hybridization of an optical cavity mode and a plasmonic mode. Fig. 1 shows a schematic of such a system composed of a gold nanorod coupled to a microtoroid. We have used finite element analysis via COMSOL to find the resonance of a nanoantenna with $R = L/D = 3$, where L is the length of the nanorod and D is the diameter. This was done to ensure that our nanorods had a resonance around 670 nm. The resonance of the nanoantenna can also be found though a simple Fabry-Perot resonator model, where a standing resonance occurs at $\lambda_{res}/2n_{eff} = L + 2\delta$, where δ represents the contribution in length from the rod's endcaps. The effective refractive index n_{eff} for the propagating surface plasmon can be found through solving the dispassion relation of the fundamental transverse magnetic (TM) mode for a golden cylindrical waveguide [16]. This model predicts the first resonance of a nanoantenna with $L = 30\ nm$ and $D=10\ nm$ to be at $\lambda_{res} = 670$ nm which agrees with our COMSOL simulation results. We note that in this work we used the gold model presented in [17].

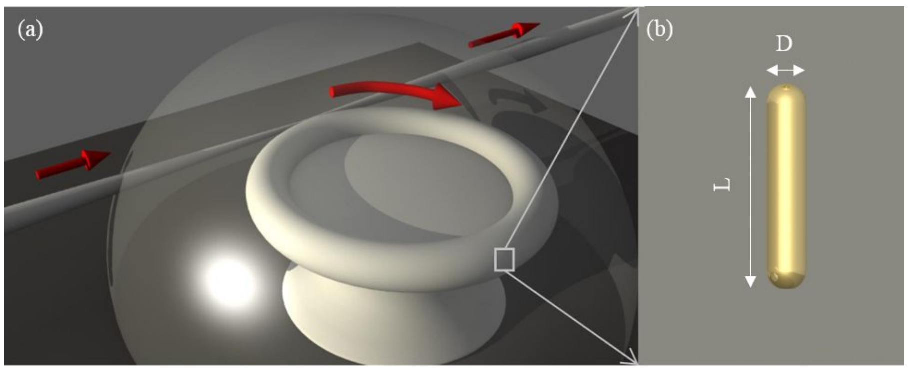

Figure 1. Schematic of a microtoroid optical resonator coupled to m nanoantennas, where m corresponds to the resonance mode of the cavity. (a) Microtoroid optical resonator with nanoparticles attached at its equator. In most experiments, light is evanescently coupled into the resonator using an optical fiber. In these simulations we do not simulate the coupling and instead just simulate two counter propagating waves. (b) An artistic rendering of a gold nanorod coupled to the microcavity.

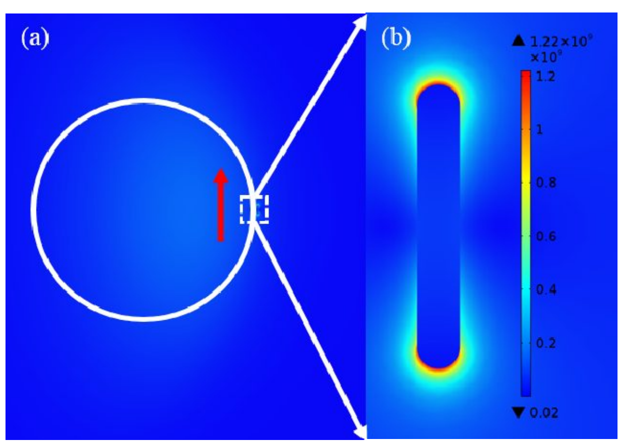

Figure 2. (a) A 3D finite element simulation of the electric field within a cross-section of a non-plasmonically enhanced (bare) microtoroid optical resonator. The red arrow shows the fundamental TE mode in the cavity. The nanorod is aligned along the same direction. The simulation is generated by simulating a pie slice of the microtoroid. (b) Electric field distribution of dipole mode for single gold nanorod. Simulation results indicate a drop of the quality factor $Q \sim 10^5$ compared to bare toroid with $Q \sim 10^7$.

To find the whispering gallery modes (WGMs) of the microtoroid and their corresponding *Q* factor, we have used the eigenvalue solver in COMSOL. The microtoroid major and minor radius are 40 microns and 2 microns respectively, and the refractive index of the cavity is $1.45+i10^{-8}$ which corresponds to silica with an imaginary part added to take into account loss due to material and surface roughness such that the simulated quality factor matches experimentally measured quality factors [5]. The surrounding material is water. This cavity supports modes with both transverse electric (TE) and transverse magnetic (TM) polarizations. We are interested in the TE mode at λ_r = 635 nm, which is close to the resonance of nanorod and the nanorod is aligned along this polarization direction to ensure optimal coupling. In our simulation, we consider *m* nanoantennas coupled to the toroid's equator, where *m* corresponds to the azimuthal mode number, and $m\lambda_r = 2\pi R_{eff} n$ where *n i*s effective mode index and R_{eff} is the effective mode radius. Using the same model in [17], it is found that the *Q* of the plasmonic cavity mode drops to 10^5 which indicates a significant loss (see Fig. 2). In the next section we presented optimized systems to overcome this issue.

3. IMPROVED PLASMONIC CAVITY MODE

Our aim is to engineer a system with almost intact *Q* and considerable surface field enhancement. To do this we have first investigated how the length of the nanorod affects the *Q* factor. From our simulations, one successful length of the nanorod is *L* = 30 nm with a diameter of *D* = 10 nm. Using this length, one can see a very high *Q* compared to a longer nanorod of 60 nm. Fig. 3 presents a comparison between *Q* factor and field enhancement for different numbers of nanorods (one 60 nm long nanorod vs two short 30 nm nanorods).

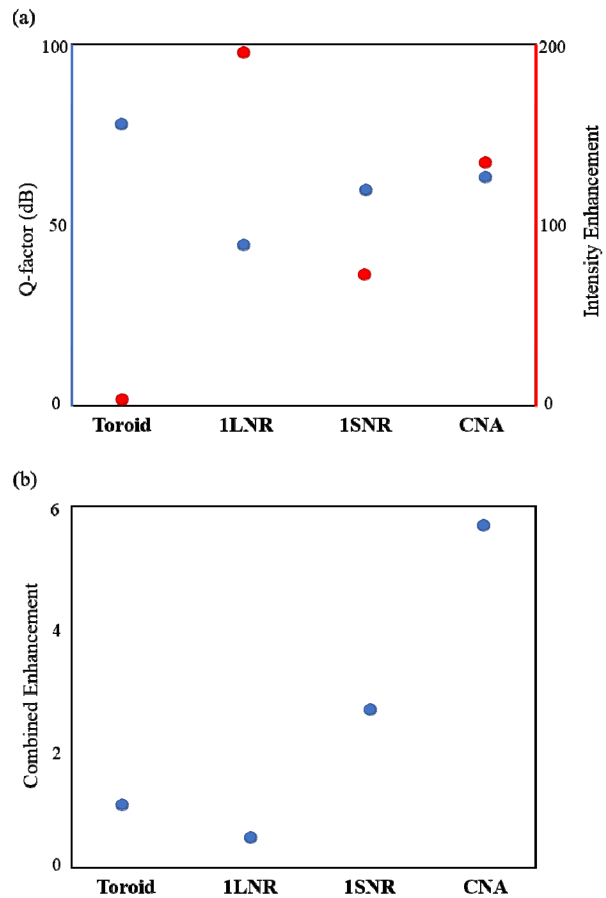

Figure 3. (a) Our simulation results indicate that using a single long nanorod (1LNR) (60 nm) leads to higher field enhancement, but that the *Q* for single short nanorod (1SNR) or two coupled nanoantennas (CNA) (30 nm each with a total combined length of 60 nm) system is higher. Blue circles represent the *Q* factor and red ones indicate the field enhancement. (b) The combined enhancement is higher for the nanogap antenna system, comprised of two shorter nanorods.

The simulation results for a system composed of two coupled similar nanoantennas (*L= 30 nm* for each nanorod) are shown in Fig. 4. Here, both the *Q* and the field enhancement of the plasmonic cavity mode are increased. Clearly two coupled nanoantennas supports higher combined enhancement.

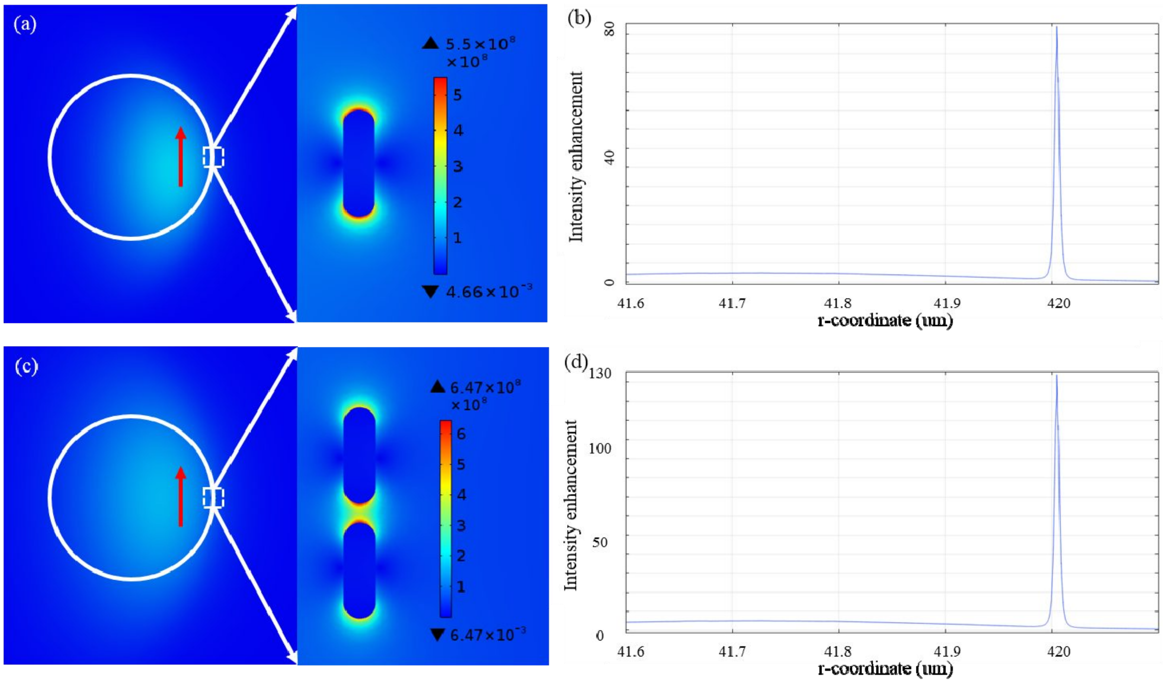

Figure 4. Electric field for system composed of (a) single nanorod (c) two coupled nanorods on the equator of a microtoroid. Intensity enhancement for (b) single and (d) coupled nanorods, respectively. The coupled dipole nanoantenna supports a hot spot in the gap between the two nanorods with a higher field intensity compared to the intensity hotspot generated at the endcaps of a short nanorod.

4. EFFECT OF DIFFERENT GOLD MODELS

Having studied different arrangements of nanoantennas coupled to microtoroids in order achieve high Q modes, it is also important to note that our results strongly depend on the gold model that we use in our simulation. Fig.5 show the real and imaginary parts of the permittivity for gold based on two common gold models presented in references [17,18].

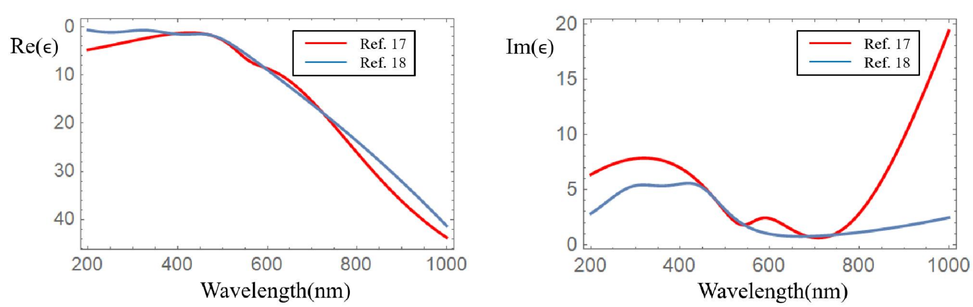

Figure 5. Real (right panel) and imaginary (left panel) parts of the gold's permittivity according to different models presented in ref [17,18].

Obviously, in certain wavelength domains these two models provide different real and imaginary values for gold's permittivity. As a result, one expects different simulation results for these two models. Table 1 indicates the calculated Q for each gold model used in COMSOL simulation. We note that the calculated Q values for ref

[18] are several orders of magnitude smaller than the other model presented in [17]. Thus, it is important to experimentally investigate these systems to find the best model which agrees with experiment.

Table 1. Comparison between simulation results based on different gold models in [17,18].

Gold model		Q-factor	Intensity enhancement	Combined enhancement
1SNR	Ref. 17	1.3×10^6	78	2.6
	Ref. 18	5.7×10^4	77	0.11
CNR	Ref. 17	1.7×10^6	133	5.8
	Ref. 18	3.6×10^4	187	0.17

5. CONCLUSION

In conclusion, we have presented an optimized nanoantenna coupled to a microtoroid system which supports ultrahigh Q plasmonic cavity modes with high field enhancement. It is shown that a coupled dipole nanoantenna system can in general support modes with $Q \sim 10^6$ and around 130 times intensity enhancement. An immediate application of the presented system is in optical biosensing where maintaining high Q is essential.

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