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Hybrid plasmonic microcavity with an air-filled gap for sensing applications

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ABSTRACT

In this paper, a novel hybrid plasmonic microcavity with air-filled regions in the low-permittivity dielectric gap is proposed for sensing applications. Compared with the conventional structure with homogeneous gap, the introduced air-filled regions could improve the key modal characteristics of the hybrid mode. Simulation results reveal that this kind of hybrid microcavity maintains low loss with high quality factor ~3062, and high field confinement with small mode volume 0.891 μm^3. Moreover, in the sensing applications, this hybrid microcavity features simultaneously large refractive index sensitivity of 100 nm/RIU (refractive index unit) and relatively high quality factor of 3062. Hence, it shows that the hybrid plasmonic microcavity has potential applications in ultra-compact refractive index sensor.

1. Introduction

Hybrid plasmonic microcavities exploiting the coupling between dielectric whispering-gallery modes and surface plasmon resonance modes have attracted significant research interests recently due to their remarkable capability to provide improved balance between confinement and loss than both the dielectric cavity and the plasmonic cavity. By introducing a low-permittivity dielectric gap between metallic and high-index semiconductor structures, these super microcavities allow efficient localization of light-waves inside gap regions, while simultaneously alleviating the Ohmic losses at metallic surfaces. Moreover, hybrid plasmonic microcavities have substantial mode confinement in the surrounding dielectric, which is of importance since it offers the effective pathway to exchange the energy between the cavity mode and the external devices. Owing to their remarkable guiding performance, people have developed various hybrid plasmonic microcavities [1–13], such as the microcavity consisting of a high-index dielectric nanoring placed adjacent to metallic surface [1], the silicon-based microcavity that comprise a metallic disk on top of silicon-on-insulator (SOI) substrate [2] and the silicon hybrid plasmonic submicron-donut resonator [10]. And numerous intriguing applications, including light sources [1], optical sensing [2,3], have been enabled based on these traditional hybrid plasmonic structures.

In terms of sensing applications, some of the dielectric cavities have been proved to be extremely useful as sensors of change in refractive index [14], which have a high quality factor and a high sensitivity. On the other hand, hybrid plasmonic microcavities have substantial mode confinement in the surrounding dielectric, which is necessary for sensing applications since it determines the light-matter interaction strength. Moreover, the hybrid plasmonic microcavity allows us to enhance the light-matter interaction and can break the diffraction limit due the effect of plasmonic. Therefore, although the quality factor and the sensitivity of the hybrid microcavity are may smaller than that of some dielectric cavities. The hybrid plasmonic microcavities are still attractive for ultra-compact bulk refractive index sensors [15,16].

In this paper, aiming at achieving a high sensitivity and a high quality factor simultaneously, we introduce a modified scheme. The quality factor and the sensitivity are on the same order of some dielectric cavities. And, in contrast to the conventional hybrid structure, the gap of the modified hybrid microcavity consists of a silica strip and air-filled regions rather than a homogeneous low-index material, thus the local field enhancement in the air-filled gap regions is strong due to the gap effect, which plays an important role in sensing applications. And our simulation results demonstrate that, besides improving the key advantages of the conventional structure, the modified scheme could offer possibilities for both high quality factor which is associated with the detection limit and high sensitivity.

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2. Structure and basics

Three-dimensional (3D) and two-dimensional (2D) geometries of the studied hybrid plasmonic microresonator are shown schematically in Fig. 1(a) and (b). The structure consists of a metallic strip ring right above a high-index semiconductor microdisk, with a modified gap composed of a low-index dielectric strip gap and air-filled regions. The width and height of the metallic strip ring are *a* and *b*, while the low-index dielectric strip gap has a width of *w* and a height of *g*. The radius and thickness of the microdisk are *R* and *t*. The materials of the semiconductor microdisk, the low-index dielectric strip gap and the metallic strip ring are silicon (Si), silica (SiO_2) and silver (Ag), respectively. It is worth mentioning that, when $w=a$, the proposed hybrid plasmonic microresonator becomes the traditional structure that has a homogeneous low-index gap. In the following, the characteristics of the studied hybrid microresonator are investigated using a finite-element method (FEM) [17] at the wavelength of 1550 nm. The permittivities of Si, SiO2 and Ag for the studied hybrid microresonator are taken as $\varepsilon_{Si} = 12.25$, $\varepsilon_{SiO_2} = 2.25$ and $\varepsilon_{Ag} = -129 + 3.3i$ [5], respectively. The surrounding medium is air whose dielectric constant is 1.0.

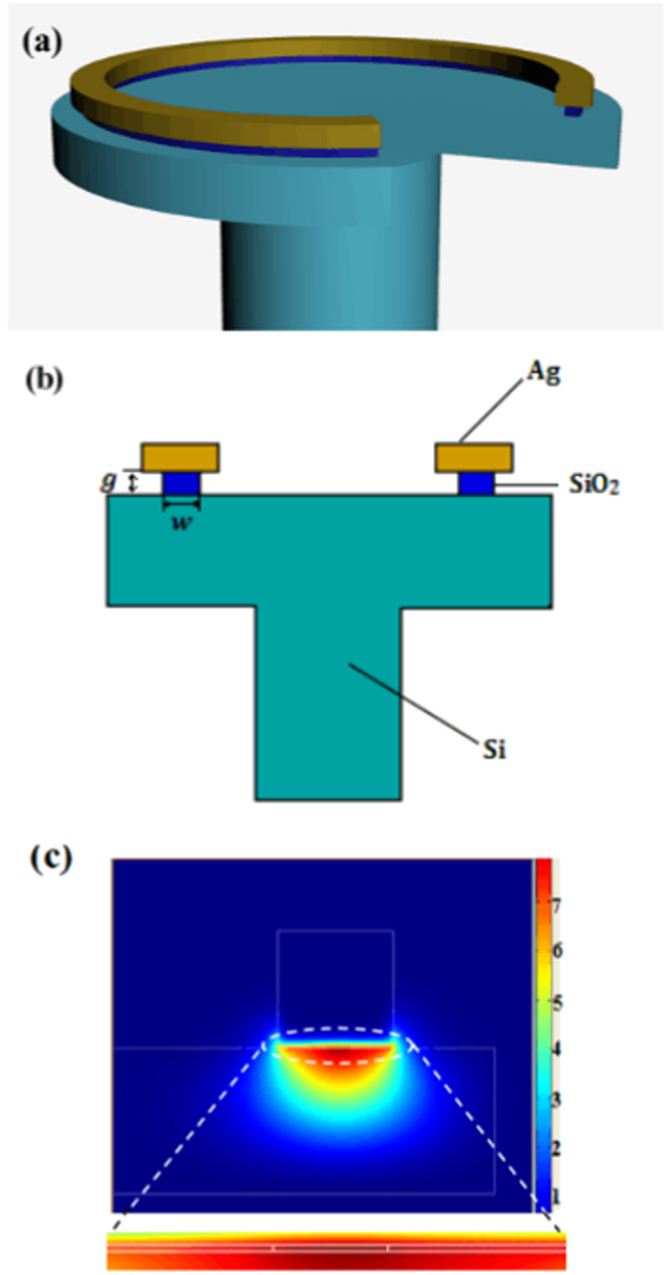

Fig. 1. (a) The structure of the proposed hybrid plasmonic microcavity; (b) the cross-section; (c) the field intensity distribution of the proposed hybrid plasmonic microcavity, inset: the magnification of the gap region.

For the proposed hybrid plasmonic microresonator, two major modes are supported: the hybrid plasmonic mode and fundamental dielectric whispering-gallery mode. Fig. 1(c) shows the field intensity distribution of the whispering-gallery-like hybrid plasmonic mode, and the inset in Fig. 1(c) is the magnification of the gap region. The hybrid plasmonic mode is a combined of dielectric and plasmonic microresonator, which offers a better compromise between the loss and confinement than the pure surface plasmon resonance mode and the pure dielectric whispering-gallery mode. Furthermore, the hybrid plasmonic microcavity have considerable energy distribution in the surrounding dielectric, this result can be understood by the hybrid mode which can attract part of the cavity energy from the silicon disk microcavity. Moreover, as shown in the field intensity distribution figure, the local field enhancement in the air-filled gap regions is strong due to the gap effect. It is expected that the air-filled gap regions may not only contribute to the reduction of loss, but also lead to a high sensitivity. Hence we only care the hybrid plasmonic mode for achieving a high quality factor and a high sensitivity.

3. Simulation results

In this section, we investigate the effect of the silica gap width on the properties of the guided hybrid plasmonic modes for the modified hybrid microresonator with different silica gap heights. The width and the height of the metallic strip ring are chosen to be $a=b=200$ nm which are typical thickness used in many hybrid structures. The radius and the thickness of the microdisk are $R=5$ μm and $t=250$ nm. The considered modal characteristics include the quality factor *Q*, the effect mode volume *V* and the energy ratio η.

By studying the temporal decay rate of the resonant modes, the quality factor *Q* associated with the cavity's photon life time is extracted for the hybrid plasmonic microresonator. The *Q* factor can be evaluated as [18]

$$Q = \mathrm{Re}(f)/2\mathrm{Im}(f) \tag{1}$$

where

$$f = f_{Re} + f_{Im} \tag{2}$$

is the complex-valued eigenfrequency. Generally, in hybrid plasmonic microresonators, two sources of resonator energy loss are mainly taken into account, i.e. the surface plasmon mode loss originating from the metal material loss, radiation loss due to the sharp bending. Potential scattering losses due to the surface roughness which can be restricted in a minimum in experiment are not considered in this simulation work. Moreover, the silicon absorption loss which is much smaller than the metal absorption loss has been left out. Hence, the numerically achieved *Q* factor of the studied structure satisfies

$$1/Q = 1/Q_{rad} + 1/Q_{abs} \tag{3}$$

which is the loss mechanism of the hybrid plasmonic mode, where Q_{rad} and Q_{abs} are induced by the metal absorption loss and radiation loss, respectively. Here we propose to utilize a perfectly matched layer to calculate the total *Q*, and the *Q* value just provides a ideal theoretical value. Specifically, for this hybrid structure with $R=5$ μm, Q_{rad} is on the order of 10^{14}, the radiation loss can be