A Simple and High-performance Platform for Refractive Index Sensing based on Plasmonic Metal Disks on a Metal Mirror

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Abstract. Numerical simulations are used to study light interactions with a platform composed of arrays of stacked metal and spacer dielectric disks on a continuous Au film. Tunable and high absorption is obtained near 1.6 $\mu$m by adjusting the thickness of the dielectric disks. Nearly perfect absorption remains for a wide range of disk diameters. The near-perfect absorption is attributed to a magnetic resonance within the dielectric disks (combined with electric resonance at the metal disks) inducing the platform response to incident light. In addition, the resonance response to environment is more sensitive than that of metal disks on dielectric/metal films. Furthermore, when the diameter of the dielectric disks is reduced, the local electromagnetic field is more exposed and the refractive index sensitivity (RIS) increases to 1133nm/RIU (refractive index unit). The method is simple and effective to improve RIS of sandwich plasmonic structures and will be adopted in various plasmonic devices.

1. Introduction

Micro/nano-scale metal particles support optical carrier resonances called localized surface plasmon resonances (LSPRs) [1,2], which are paid much attention in various fields, such as light harvest[3], gas sensing [4], molecular sensing [5-7] and surface enhanced Raman scattering [8]. One area of strong interest concerns optical refractive index sensing based on spectra shifts of resonances in response to refractivity change of the surrounding environment. Refractive index sensors are widely used in testing the amount of specific materials in solution and identification of types of gas and solutions [4, 9, 10]. It is a vital method for the sea economy and chemical industries. There are several strategies for refractive index sensing, such as utilizing propagate surface plasmon polariton resonances (PSPR), plasmon lattice resonance (PLR), Fano resonance or Fabry–Perot (FP) cavities to achieve high-sensitivity sensing [11]. Recently, the Bin Ren group suggested a unique two-dimensional gold plasmonic nanohole array, which presented a PSPR with full width at half maximum (FWHM) of 8nm and figure of merit (FOM) of 730 [12]. Jianfang Wang’s team fabricated plasmonic gold mushroom arrays, whose RIS approaches 1010nm/RIU and FOM is 108 [13]. Hatice Altug’s group demonstrated a Fano resonance asymmetric metamaterial, which can be used to identify molecular monolayers [14]. However, sensors based on PSPR, PLR and Fano resonance usually need well-ordered micro/nano-structure arrays, which is a challenge for manufacturing technology due to high cost. In addition, simple nanostructures and disordered or short range ordered nanostructures also show high-performance sensing and are easy to fabricate. For examples, monolayer metal disks array fabricated
by microsphere lithography shows resonance linewidth of 10.5nm and FOM of 15.3 [15]. When metal
disks are separated by dielectric disks, placed on glass substrates, it shows improved RIS of
800nm/RIU [16]. When wet etching is implemented to the supporting dielectric pillars of these kinds
of structures, the obtained sensor can expose more area to local environment, resulting in further
improved sensing performances [7]. Such methods via reducing substrate effect on sensing
performance of metal disks and increasing exposed area show potential for more sensors. In addition,
we find metal/dielectric/metal structure can easily obtain high absorption, via FP-like cavities [17, 18].

To design a high-absorption and high-performance RI sensor, a platform composed of Au/SiO₂
disks placed on a continuous reflecting Au layer is suggested. By optimizing the thickness of the SiO₂
disk, tunable prefect absorption is achieved. The RIS of the suggested structure is two times higher
than that of Au disks placed on continuous SiO₂/Au film [19]. When the diameter of spacer SiO₂
disk is reduced, the RIS can reach 1133nm/RIU. These results provide a new design that can be utilized in
high sensitivity detection.

2. Design and Numerical Study
A schematic representation of the suggested platform is shown in figure 1. The platform is composed
of Au/SiO₂ disks on top of a reflective Au layer. CST microwave studio software was utilized to
calculate the electromagnetic distribution and absorption. The Au/SiO₂ disk and bottom Au layer were
placed at the center of coordinate space and the z=0 for the interface between Au disk and SiO₂ disk.
Their geometric center was set at the z axis. The boundary of the Au square was parallel to the x and y
axis. As the platform is symmetrical about xoz and yoz planes, symmetry planes were set to reduce
mesh and calculation time. In addition, there is no PSPR and PLR existing for the structure, so a single
disk placed on Au mirror is feasible as a design. In the simulation, the environment index was 1.33 or
1.33~1.36. The side length of the Au mirror was fixed at 550nm. The thickness of the top Au disks
was fixed at 20nm, while other parameters such as the radius of the Au/SiO₂ disks, the thickness of the
SiO₂ disks, and the radius of SiO₂ disks were adjusted to find a better set of parameters which promise
a better sensing performance of the structure. The Au mirror thickness was 100nm, where no light
from visible light to near-infrared light can transmit through it. The incident plane wave transmits
along the z axis, with electric vector along the x axis. Optical constants were taken from Ref. [20].

![Figure 1. Scheme of the simulation unit.](image)

2.1. Thickness of Spacer Layer Effect on the Absorption Spectra
To achieve high absorption, the thickness of SiO₂ was varied. The initial value of disk radius was
140nm. The absorption spectra varied with the thickness of the spacer SiO₂ disks layer as shown in
figure 2. With the increase of the SiO₂ thickness, the resonance shifted to shorter wavelength. The
amplitude of absorption initially increased, went through a maximum, and then decreased. The process
is adjusting of FP-like cavity mode (magnetic resonance) among SiO₂ disks. A proper thickness of
SiO₂ disk will meet perfect absorption.
2.2. Radius of Disk Effect on the Absorption Spectra

Based on the results seen in figure 1, we set the thickness of the SiO$_2$ disk to 30nm to keep a high absorption in following calculations. Here, the radius of both the Au/SiO$_2$ disks was varied from 125nm to 160nm, with a step of 5nm. The peak position shifted to longer wavelength quickly, and the FWHM of peaks in wavelength increased concomitantly with the increased radius, as shown in figure 3 as expected for larger metal particles. We also noticed that the perfect-absorption does not alter during this tunability. The high absorption is attributed to a magnetic resonance located in spacer SiO$_2$ disks, which dominates the platform’s response to incident light.

2.3. Spectra Response to Surrounding Environment

![Figure 3. The absorption spectra varying with Au/SiO$_2$ disks radius.](image)

![Figure 4. Spectral response to environment.](image)
To compare with results in Ref. [17], we selected radius of the Au and SiO$_2$ disks of 140nm, whose absorption peak was near 1.6 $\mu$m. The resonance peak shift is present in figure 4. The environment index was varied from 1.33 to 1.36 and the peak-shift was 24nm corresponding to a RIS of 800nm/RIU, which is twice as large as the RIS result reported in Ref. [17].

3. Improving Spectra Sensitivity to Environment by Increasing Exposing Area
To expose more local electromagnetic field, here the spectra response to change in the environment refractive index with reducing diameter of the SiO$_2$ disk was studied. The resonance peak shift is shown in figure 5(a) and (b). The RIS was 1000nm/RIU and 1133nm/RIU, respectively for SiO$_2$ disks diameter of 80nm and 60nm. These results validate that increasing the exposed area is effective for metal/dielectric/metal microstructure to improve sensing performance. Figure 5(c) and (d) presents electric field and magnetic field distribution of XOZ plane ($y=0$nm) at the resonance wavelength observed in figure 5(b) with bulk refractive index of 1.33, which indicates that the high absorption results from the magnetic resonance located in the SiO$_2$ disk [17]. The local field distribution revealed near the SiO$_2$ disk is the reason for the improved RIS.

![Figure 5](image)

**Figure 5.** (a) and (b): Spectral response to change in the local dielectric environment, the radius of SiO$_2$ disks is 40nm and 30nm, respectively. (c) and (d): electric field and magnetic field images of XOZ plane ($y=0$nm), related to (b). The $z$ value is inverted in (c) and (d).

4. Conclusion
A simple and high-performance sandwich structure plasmon refractive index sensor is suggested. The platform is with near-perfect absorption at a resonance peak due to a hugely enhanced magnetic resonance inducing response to incident light. Improved RIS of the sensor is validated via increasing expose area of local magnetic resonance. In detail, by replacing spacer dielectric layer with a dielectric disk, and further reducing the diameter of the dielectric disk, the RIS of 800 nm/RIU, 1000 nm/RIU and 1133 nm/RIU are obtained, respectively. The high-performance sensor can find application in RI test and solution identification.
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