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Using Babinet's principle in plasmonics for dielectric sensing

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Abstract

Plasmonic structures that exhibit localized surface plasmon (LSP) resonances have been exploited in multiple applications including sensing, medicine, and chemistry. LSPs resonances appearing in, for instance, periodic/aperiodic rods or spheres have been recently used for sensing due to the fact that such resonances are sensitive to local external variations such as changes in the refractive index of a dielectric placed on top of them. In this communication, we make use of complementary plasmonic structures (exploiting the Babinet's principle) consisting of metal-dielectric cylindrical components to study their performance as dielectric film sensors. An in-depth comparison of the complementary structures with the original plasmonic configurations is carried out demonstrating the advantages/disadvantages of each design.

1 Introduction

In recent years, research and innovation exploring metallic surfaces for surface plasmons polariton-based devices [1]–[4] and nano-/microstructures acting as plasmonic nanoantennas [5]–[7] has increased due to their ability to strongly confine incident electromagnetic (EM) fields in the visible and near-infrared regime, achieving subwavelength spatial resolutions [8]–[14]. Plasmonic structures enable this EM field confinement due to the excitation of LSPs resonances [7], [8], [15]–[18], which have recently been applied in areas such as solar cells [19], optical trapping [20] and photo-catalysis [21], among others.

LSP resonances appearing in plasmonic nanostructures are highly dependent on a number of parameters such as the shape of the plasmonic particles [22], [23] and the materials involved in their design [24], [25]. This dependence causes observable shifts in the spectral position of LSP resonances, for instance, when the refractive index of a dielectric near the metallic structures, n_a, is modified. It is this sensitivity to external changes that allows LSP resonances to be used in many different sensing applications, including in biosensing [26], [27] and other areas such as surface-enhanced Raman spectroscopy [28], [29], among others.

There have since been pioneering works further exploring LSP concepts by applying well-known classical optics concepts to the realm of plasmonics. An example of this is the use of the Babinet's principle (first developed at low frequencies [15]) for the design of plasmonic structures [6], [22], [30]–[33]. Babinet's principle states that the diffraction pattern from a set of infinitely thin, perfectly opaque particles will be identical to a complementary set of apertures in an infinitely thin, perfectly opaque sheet [34]. In this context, the respective near-field magnetic and electric field distributions will be interchanged between particle and aperture cases. Recently, it has been proposed that this concept could be applied to plasmonics with LSP resonances also occurring at the same frequency for complementary structures [16], [30]. It must be noted that some slight discrepancies will occur when this principle is applied to plasmonics due to metals at optical frequencies cannot be considered as perfect electric conductors as it is the case for low frequency [22].

In this communication, we study the performance of complementary plasmonic structures consisting of double cylindrical metallic particles and apertures with a thin dielectric film positioned atop the plasmonic structures [35]. The refractive index of the dielectric film is then varied and the sensing performance of the two complementary plasmonic structures is compared. An in-depth study of their performance will be discussed during the conference.

2 Results and discussion

In Fig. 1, schematic representations of the devices are shown, each consisting of double cylindrical metallic (gold, Au) features on a substrate (silicon nitride, Si_3N_4). Fig. 1a,b show the top (on their surface) and cross-section representations of the two Au particles, respectively. Fig. 1c,d represent the same as Fig. a,b but considering the cylindrical apertures (complementary structures). The Au and Si_3N_4 layers each have a layer thickness of 30 nm with the materials modeled using experimental data from [36],

[37], respectively. Positioned atop the metallic components is a film of a dielectric with a refractive index, n_a, which is considered to be the analyte to be sensed. This entire structure is immersed in air (n_{air} = 1). In Fig. 1b,d, the parameters of the two cylinders are presented where *D* is the diameter of the particles and *S* is the separation distance between the two cylinders.

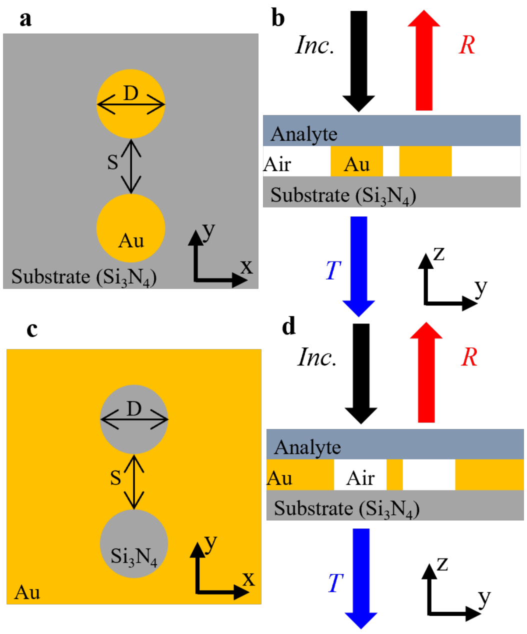

Figure 1. (a,b) Schematic representation of the two gold cylindrical particles on a silicon nitride substrate: top and cross-sectional view, respectively. (c,d) same as (a,b) but the complementary structure using cylindrical apertures in a gold sheet. *D* and *S* represent the diameter of the cylindrical features and the separation between the two cylinders, respectively. An analyte (to be sensed) is placed on top of the plasmonic structures and has a thickness of 100 nm. The refractive index n_a of this analyte will vary to evaluate the sensing performance of the proposed structures. Both plasmonic structures are illuminated by an incident planewave (black) and the reflection (red) and transmission (blue) scattering parameters are measured.

The structures shown in Fig. 1 were numerically simulated using COMSOL Multiphysics®. They were illuminated using an incident planewave polarized along the *x* (E_x) or *y* (E_y) direction (as represented by the black arrow labelled *Inc.* in Fig. 1b,d). Illuminating the structures with the two different polarizations result in different, complementary LSP resonances being excited for each of the plasmonic structures (particles/apertures). To determine the spectral position of the LSP resonances, the scattering parameters across the spectral range of each case were calculated. These are represented in Fig. 1b,d by the red arrow for the reflection, and the blue arrow for the transmission. As the LSP resonant frequency is sensitive to external changes, such as changes of the n_a of the dielectric, an observable spectral shift of the LSP resonance will be expected, enabling these devices to be used as a sensor.

In this communication, *D* = 200 nm and *S* = 20 nm for the cylindrical features and the dielectric analyte positioned atop the metallic structures had a thickness of 100 nm. A single thickness of analyte is chosen so the only variations in the LSP resonant frequency will be a result of changes in the n_a. Therefore, this can be used to determine the sensitivity of each configuration of the plasmonic structures as the spectral frequency shift will be strongly linked to the value of n_a for the analyte. This was done by taking the ratio between the change in the LSP resonant wavelength and the change in the refractive index of the analyte, $S = \frac{\Delta\lambda}{\Delta n_a}$ [nm/RIU]. The sensitivity of the two complementary plasmonic devices under complementary illumination as n_a varies is shown in Fig. 2. Apertures and particles are shown as red and blue curves, respectively, with E_x illumination represented as solid lines and E_y represented as dashed lines. The complementary nature of the plasmonic structures can be studied by looking at their performance under complementary illumination. In this case, the particles/apertures were first illuminated with a E_y/E_x polarized planewave. From Fig. 2, the maximum sensitivity values (S_{max}) are S_{max} = 357/399 nm/RIU for the particles/apertures, respectively. Then, the orthogonal polarization was used for both structures such that particles/apertures were now illuminated with a E_x/E_y polarized planewave, respectively. For this scenario, values of S_{max} = 341/303 nm/RIU were obtained, respectively, meaning that, overall, S_{max} is increased when using E_y/E_x polarized planewaves. Such improved performance can be attributed to the different LSP modes being excited under different polarizations which, as it will be shown during the conference, the E_y /E_x polarized planewaves illuminating the particles/apertures produce a field hotspot that enhances the interaction with the dielectric analyte compared to the field distribution of LSP modes under orthogonal polarizations.

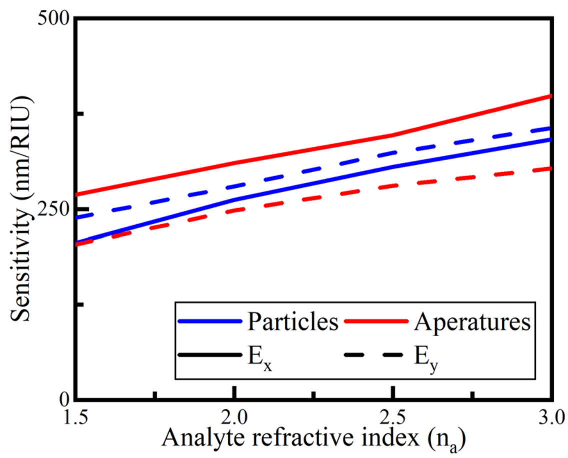

Figure 2. Sensitivity of the particle (blue) and aperture (red) structures illuminated by an E_x (solid) and an E_y (dashed) polarized planewave as the refractive index of the dielectric analyte changes

Further details will be presented at the conference including an exploration into the nature of the complementary near-field distributions and the effect of the thickness of the dielectric layer on the sensing performance. Furthermore, comparisons to experimentally fabricated devices will be made to verify the validity of our work.

3 Conclusion

To conclude, in this communication the well-known Babinet's principle for complementary structures has been applied to plasmonic structures to design complementary metallic structures capable of supporting LSPs resonances. These structures were illuminated by complementary polarized incident planewaves exciting different LSP modes depending on the polarization of the illumination. The spectral positions of the LSP resonances were used to sense variations in the refractive index of a 100 nm thick sheet of dielectric analyte which was positioned atop of the metallic structures. The performance of these plasmonic-based sensing devices was then determined by calculating the sensitivity as the refractive index of the analyte varied, showing sensitivities of 200 nm/RIU up to 400 nm/RIU. Full details will be shown at the conference exploring the effect of variations of the dielectric thickness and different analyte configurations as well as our recent experimental efforts on demonstrating the hotspots and field distributions of the different LSP modes excited in the plasmonics particles and complementary apertures. Our results may be exploited in sensing devices within areas such as biology and chemistry.

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