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Advanced refractive index sensor using 3-dimensional metamaterial based nanoantenna array

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Advanced refractive index sensor using 3-dimensional metamaterial based nanoantenna array

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Abstract. Photonic researchers have increasingly exploiting nanotechnology. Due to the advent of numerous prevalent nanosized manufacturing methods that enable adequate shaped nanostructures to be manufactured and investigated as a method of exploiting nano-structured. Owing of the variety of optical modes, hybrid nanostructures that integrate dielectric resonators with plasmonic nanostructures also offer enormous potentials. In this work, we have explored a hybrid coupled nano-structured antenna with stacked lithium tantalate ($LiTaO_3$)/Aluminium oxide (Al_2O_3) multilayer operating at infrared ranging from 400 nm–2000 nm. Here, the sensitivity response has been explored of the hybrid nano-structured array made up of the gold metal elliptical disk placed on the top of a quartz substrate and excite the different modes in both materials. It shows large electromagnetic confinement at the separation distance (*d*) of the dimers due to strong surface plasmon resonance (*SPR*). The influence of the structural dimensions is investigated to optimise the sensitivity of stacked elliptical dimers. The designed hybrid coupled nano-structure with the combination of gold (Au) and Lithium tantalate ($LiTaO_3$) /Aluminium oxide (Al_2O_3) with h_1 = h_2 = 10 nm each 10 layer exhibits bulk sensitivity (*S*), which is the spectrum shift unit per refractive index (*RI)* change in the surrounding medium was calculated to be 730 and 660 nm/RIU with major axis, (*a*) = 100 nm, minor axis, (*b*) = 10 nm, separation distance (*d*) = 10 nm, height, (*h*) = 100 nm (with or without stacked). The outcomes from the proposed hybrid nanostructure have been compared with a single metallic (only gold) elliptical paired nano-structure to show a significant improvement in the sensitivity using hybrid nano-structure. Depending on these findings, we demonstrated a roughly two-fold increase in sensitivity (*S*) by utilising a hybrid nano linked nano-structure with respect to identical nano structure, which competes with traditional sensors with the same height, (*h*) based on localised surface plasmon resonances. Our innovative plasmonic hybrid nanostructures provide a framework for developing plasmonic nanostructures for use in various sensing applications.

Keywords: Nano-antenna, Surface plasmon resonance, plasmonic sensitivity, plasmons, refractive index sensing, and Localized surface plasmon resonance.

1. Introduction

Researchers have become more interested in surface plasmon polaritons (SPPs) over through the decades since they provided a fresh, remarkable direction for the future era of nanotechnologies. The progress of optics includes the integration and miniaturization of optoelectronic circuitry and subsystems. To construct effective nano photonic devices [1] with ultra-fast operational speed and the capability to concentrate the electromagnetic field into a region significantly narrower than the operating wavelength [2], using SPPs ensures that the objectives of the nanophotonic branch [3] are addressed. SPPs have amazingly been used in several technologies, including waveguides [4], modulators [5], nano-lasers [6], and nano-antennas [7].

Initial studies with nanosized antenna focused primarily on controlling the localized incident electromagnetic pattern while responding with electromagnetic radiation that were incident from free space or a point source. Multidisciplinary devices are essential in deployment situations involving detectors and spectroscopy instruments. However, when equipment is being created for optics, the antenna would need to be able to take an electromagnetic signal in-plane, broadcast it to space, and, via reciprocity, would need to be able to receive the data from space and transmit it in-plane. Due to advancement of semiconductor fabrication techniques and electron beam lithography, researchers have lately delved into the manufacture of nano-antenna [7], which range in size from a few hundreds of nanometers over several microns. These may be advantageous because of their rapid transient response, compactness, and efficiency parameters adjustability. However, since metals become dispersive inside the visible region and must be simulated with accurate dielectric permittivity, optical antenna modeling calls for further caution. While the dielectric resonator was used to create the antenna described in [8], most nanoantenna working in the optical regime rely on the plasmonic resonance principle [9-10], and [11]. In addition to these methods, hybrid plasmonic structures have been used to build nano-antennas [12-13]. Yousafi *et al.* [14] have suggested a rectangular patch nano-antenna to release the localized electromagnetic wave power of a hybrid plasmonic waveguide [15-17] in which the electromagnetic waves were contained in thin material having very low refractive index in between a plasmonic metallic layer and a high refractive index material. Unfortunately, the applicability of surface plasmons polaritons (SPPs) for many real-world applications is considerably restricted by their substantial signal attenuation. To attain long propagation length by fusing the dielectric and plasmonic antenna, the hybrid plasmonic mechanism has been employed for nano-antenna design.

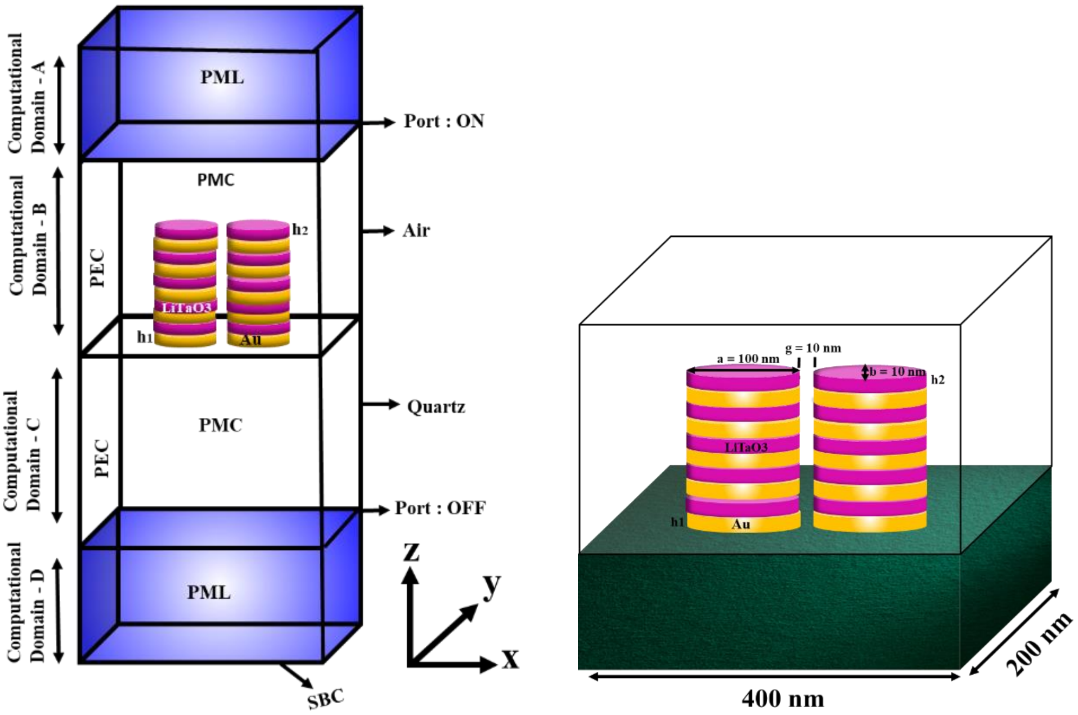
In this paper, we have proposed a noble hybrid with Lithium Tantalate ($LiTaO_3$)/Aluminum Oxide (Al_2O_3) multilayer stacked elliptical shape paired nanoantenna as they can confine and maintain surface plasmon polaritons (SPPs) operating at infrared region ranging from 400 nm–2000 nm. This paper is divided into four sections where Section II describes the computational design and optimization methods. Section III evaluates the parametric studies of the multi-layer structure. Finally, in Section IV a conclusion and future possibilities are drawn.

2. Approaches for computational design and optimization

In this paper, the Comsol Multiphysics software enabled with Finite Element Method (FEM) has been used to calculate the plasmonic response and to design the coupled hybrid nano structured antenna as displayed in Fig. 1. Fig. 1(a) shows a 3D view of the schematic of designed computational domain of hybrid nanostructured antenna. The metal (gold) properties have been calculated using the Drude-Lorentz model as it is based on the movement of the unbounded electrons in the metal that causes the surface plasmon resonance. The properties of the material $LitaO_3$ and Al_2O_3 have been obtained for the Moutzouris *et al.* [18] and Boidin *et al.* [18], respectively. To cut the computational time, we have designed the unit cell that enforces the periodicity in x and y directions. In the computational domain the Perfect Magnetic Conductor (PMC) has been used along the x-axis and Prefect Electric Conductor (PEC) has been employed along the y-axis. To control the back reflection, the Perfect Matched Layer (PML) has been used along the z-direction to calculate the accurate computational results. The quartz substrate has been optimised at 400x200 nm^2 length and width, respectively. A hybrid nano antenna has been excited through the x-polarised light in z-direction from the top of the antenna as shown in Fig. 1a. The final design of the 10 layered hybrid sensor system placed on the 400x200 nm^2 SiO_2 is shown in Fig. 1(b). In this article we have calculated the sensitivity of the paired hybrid nanoantenna and compared with single metallic nano antenna. To calculate the sensitivity, the following equation have been used.

$$S = \frac{-\delta\lambda_{res}\ nm}{\delta n_s\ RIU} \tag{1}$$

Where, λ_{res} is the shift of the plasmonic wavelength and n_s is the souring refractive index per unit area. The performance of the designed sensor has been optimized at different RI values from 1.0 to 1.7 and then it has been observed that at each RI the resonating wavelength is shifted from 800 nm to 1600 nm. The sensitivity was calculated by the shift of the transmission spectra with respect to the wavelength. Finally, with the help of the Eq. 1 the sensitivity values have been calculated in the infrared region from 800 nm to 1600 nm.



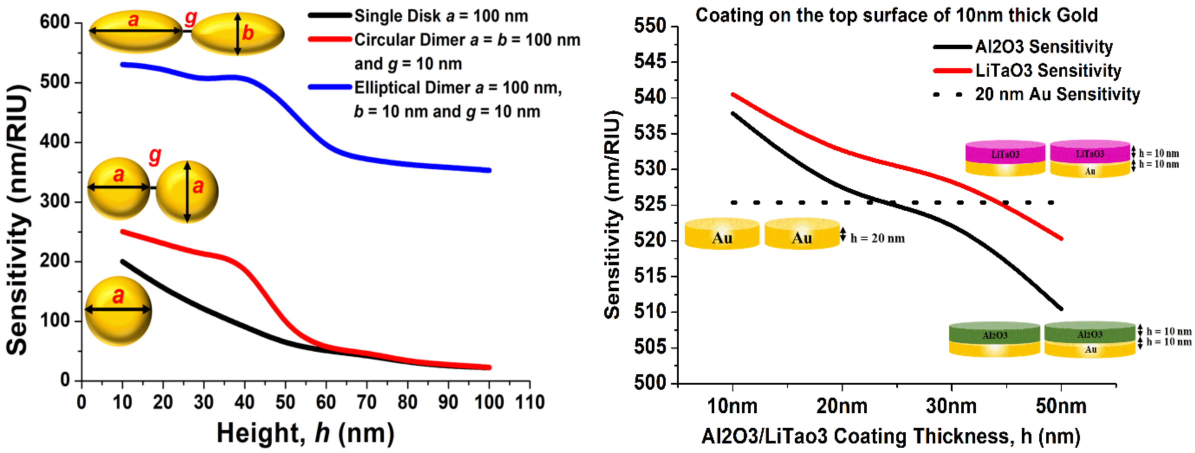
(a) (b)

Figure. 1 (a) Schematic of the computational domain designed on the FEM method enabled commercial software (b) Graphical representation of the designed hybrid Refractive index sensor.

3. The parameterized investigation of the multi-layered structure

In this section, we have analysed the performance of the hybrid nano structure with respect to the single metal nano structure. Fig. 2a shows the sensitivity comparison of the single, paired circular and paired elliptical metallic nano structures. Where black curve shows the sensitivity values nearly 200 nm/RIU of the single nano disk when a = 100 nm and h = 10 nm which reduces as h reduced and reached up to 5 nm/RIU. The response of the paired circular nano antenna when a = b = 100 nm and g = 10 nm has been shown by the red curve where the highest sensitivity 250 nm/RIU was achieved when h = 10 nm and sharply reduces at lower h values. The sensitivity response of the paired elliptical shaped antenna has been shown by the blue curve when a = 100 nm, b = 10 nm, and g = 10 nm. The blue curve shows the highest sensitivity values nearly 525 nm/RIU at h = 10 nm and gradually decreases at higher h values. In all cases, it can be observed that the highest sensitivity of single metal can be achieved nearly 525 nm/RIU and this reduces as the height of the antenna raises so to enhance further sensor performance the layer of $LiTaO_3$ and Al_2O_3 has been placed on top of the metallic paired nano antenna when a = 100 nm, b = 10 nm, g = 10 nm, and h_1 = 10 nm.

Fig. 2b shows the sensitivity comparison of the paired gold elliptical shaped antenna and the $LiTaO_3$ and Al_2O_3 stacked antenna when a = 100 nm, b = 10 nm, g = 10 nm, and h_1 = 10 nm. Black dashed curve shows nearly 525 nm/RIU sensitivity of single gold elliptical shaped antenna when h_1 = 10 nm and h_2 = 10 nm. On the other hand, when $LiTaO_3$ and Al_2O_3 was placed on the top of paired elliptical shaped antenna the sensitivity has been first increased and reaches up to 543 nm/ RIU (shown by the black curve) and 532 nm/RIU (shown by the red curve) respectively, for $h_2 = 10$ nm. From this it can also be stated that as the height h_2, of the $LiTaO_3$ and Al_2O_3 layer increases, the sensitivity is decreasing so there is no point to increase the height, h_2 of the upper layer but as the height, h_2 of the $LiTaO_3$ and Al_2O_3 is reducing the sensitivity increases. Hence, the height, h_2 of the $LiTaO_3$ and Al_2O_3 layer is fixed at 10 nm for further observations.

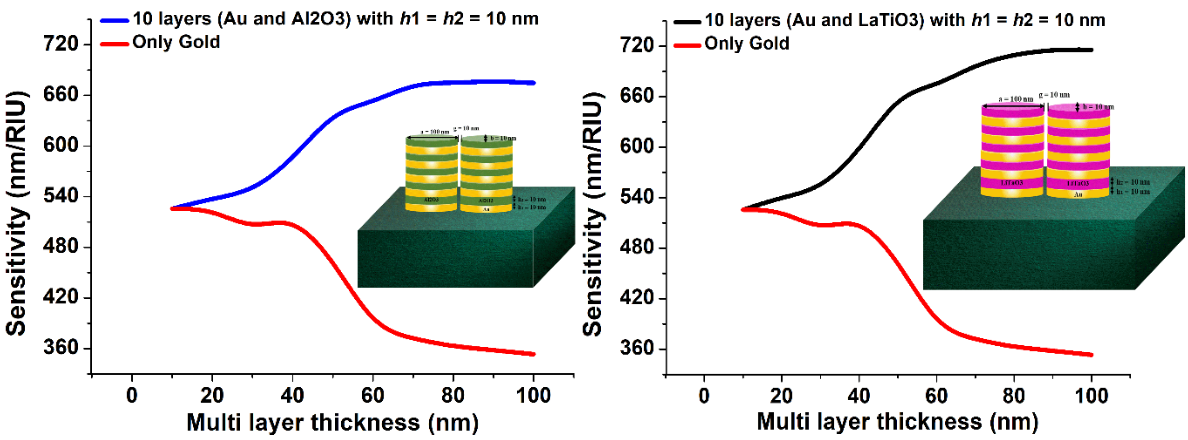


(a) (b)

Figure 2. (a) Shows the performance of the single, coupled circular and coupled elliptical shaped gold nano antenna (b) Shows the sensitivity performance of the two-layer hybrid nanoantenna.

3.1 Performance of the ten layered elliptical shaped antenna stacked with Al_2O_3 and $LiTaO_3$

In this section, we have shown the sensitivity performance of paired elliptical shaped antenna designed with gold when $a = 100$ nm, $b = 10$ nm, $g = 10$ nm, and $h = 100$ nm. Red curve in Fig. 3a shows the sensitivity values when height, h varied from 10 nm to 100 nm for single metal antenna. From this figure it can be said that at the lowest height, $h = 10$ nm the sensitivity of the single metal antenna was achieved to its highest value nearly 525 nm/RIU. However, as the height, h is increasing, the sensitivity decreases and reaches its lowest values nearly 360 nm/RIU. Where the blue curve shows that as number of the layers in the stacked antenna (with Al_2O_3) with $a = 100$ nm, $b = 10$ nm, $g = 10$ nm, $h_1 = 10$ nm, and $h_2 = 10$ nm increasing the sensitivity increases and reaches up to its saturation point nearly 660 nm/RIU. In other words, it can be concluded that by using Al_2O_3 stacked antenna the sensitivity can be enhanced by 1.5 times as compared to single metallic antenna.



(a) (b)

Figure 3. (a) Shows the performance of the single, coupled circular and coupled elliptical shaped gold nano antenna (b) Shows the sensitivity performance of the two-layer hybrid nanoantenna.

On the other hand, Fig. 3b demonstrates that by using 10 layered $LiTaO_3$ stacked antenna with *a* = 100 nm, *b* = 10 nm, *g* = 10 nm, h_1 = 10 nm, and h_2 = 10, sensitivity can be enhanced more than two folds (nearly 730 nm/RIU) as compared to the single metallic antenna. It is worth noticing the remarkable more than two-fold increase of the sensitivity and the highest electromagnetic field confinement that has been observed by using the stacked antenna approach. The enhanced intensity of the hybrid $LiTaO_3$ and Al_2O_3 was found approximately $3.5x10^3$ V/m and $2.0x10^3$ V/m respectively, which was nearly two-fold with respect to the single metallic nano structure. Hence, such $LiTaO_3$ and $Al2O_3$ stacked plasmonic sensor can detect the small change in the surrounding medium with a sensitivity of about 730 nm/RIU and 660 nm/RIU, respectively and its sensitivity is expected to increase further by decreasing the size of the antenna and the corresponding separation distance.

4. Conclusion

In conclusion, we have reported the study of hybrid ($LiTaO_3$ and Al_2O_3) stacked metallic nano plasmonic sensor. The designed and optimised sensor with *a* = 100 nm, *b* = 10 nm, *g* = 10 nm, h_1 = 10 nm, and h_2 = 10 nm has been evaluated in various surrounding refractive indexes from 1.0 to 1.5 to calculate the corresponding sensitivity. The transmission, absorption, reflection spectra and modal field profiles have also been calculated to observe the sensor performance and will be included in the extended version of the paper. The designed hybrid sensor has been compared with single metallic nanoantenna when *a* = 100 nm, *b* = 10 nm, *g* = 10 nm, and *h* = 100 nm to observe the sensitivity enhancement. From the above shown results, it can be stated that the sensitivity can be enhanced nearly 1.5 times by using Al_2O_3 stacked antenna and more than two times by using $LiTaO_3$. The effect of the separation distance has also been studied and shows highest sensitivity for smaller separation distance. The electric field confinement around the $LiTaO_3$ and Al_2O_3 stacked antenna was stronger nearly $3.5x10^3$ V/m and $2.0x10^3$ V/m respectively, which was approximately more than two-fold from the single metallic nanostructure. The proposed nano-enhanced antenna's sensitivity was proven by the outcomes of a full-wave electromagnetic simulation. Our suggested nano-antenna may be used for different nano inter- and intra-chip photonic sensor systems to develop cutting-edge detecting devices for measuring the purity of water, air, and soils. Furthermore, due of its wide frequency coverage, this suggested antenna may be employed for optical energy harvesting (also known as nano-rectenna or Nantenna) and optical sensing applications.

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