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Hollow plasmonic high Q-factor absorber for bio-sensing in mid-infrared application

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ABSTRACT

High Q-factor elements have been noticed for detecting biological particles with more accuracy, and in this current research, we have noticed a High Q- Factor absorber for bio sensing and as the first result we have confirmed that the higher Q- Factor is given more figure of merit in the presence of various biological materials. A parametric study has been revealed that how the dimensions effect the resonance of the absorber and the reflection. Finally, based on the manner of surface plasmon in absorbers in the interface of the metal and dielectric layer, we have developed an optical sensor by implementing a thin layer of active material. Therefore, the final structure is useful for bio sensing and energy harvesting applications. Our results revealed that the absorber particle enhanced the Absorption Cross Section for final model with an active layer of InGaAsSb and the current is increased more than 4 times in comparison with the case that we do not have any cylindrical particle.

1. Introduction

The photon energy is being absorbed by free electrons in the metal when the electromagnetic wave is radiating to the metal surface at the frequencies higher than Plasmon frequency which is the resonance frequency of the electrons. At these frequencies there is a nonlinear response in the metal-dielectric layer and we have collective oscillations of electron charges movement which these charges are containing photon energy and are called Polaritons [1]. Since this collective Polaritons are placed in the interface surface of the metal and dielectric, they are called Surface Plasmon Polaritons (SPP) [2]. This nonlinear optical manner of the metal layer is attractive for energy enhancement in optical devices such as plasmonic absorbers [3] and Nano-antennas [4]. The energy Absorption of the electromagnetic wave has been noticed for a wide range of practical applications in optical regime [5]. The absorber particles have been used in a wide range of the electromagnetic spectrum such as Terahertz (THz) [6] and microwave region [7], for example they are potential to be used in stealth aircrafts by reducing the radar cross section (RCS) [8]. These microwave absorbers receive the energy of microwave radiations and convert it into heat by high attenuation [9].

The absorbers are being applied in Terahertz (THz) [10], infrared (IR) [11], and optical spectrum [12] for various applications such as photodynamic therapy in cancer cells [13], biochemical sensing based on surface-enhanced Raman scattering (SERS) [14], cancer early detection [15], optical hologram [16] and wavelength selective IR sources [17].

Metamaterial has established novel kind of Electromagnetic absorbers and on the other hand, the plasmonic nanostructures have enabled spectrally selective absorption at infrared and optical range [18]. Accordingly, controlling and manipulating the absorption attributes of materials in the IR range are important for new advances in biological applications [19].

For absorber designing, various models of Nano-particles are suggested based on the application of the absorber such as bio-sensing and solar cells [20–24]. Recently, 3D structures have also been studied for various applications such as absorbers layer and Nano-antenna based on Fano resonance [25,26].

3D Nano plasmonic hollow cylindrical structures are also applied for absorbing electromagnetic wave. These structures utilize the Fano resonance to provide high values of Figure of Merit (FOM) and contrast ratio for material recognition that will be appropriate for slow light and

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broadband bio-sensing applications [27]. The optical response of the cylindrical particles can be tuned and optimized by radius and height of these particles for enhancing the absorption of optical signal and fortunately fabrication of these structures becomes possible with novel lithography techniques [28]. In addition, the process of the fabrication is described in details for these kinds of structures, by Altug et.al [29]. These kinds of nano particle for various applications at optical regime have been focused and two different types of filled and hollow structure have been developed with and without spacer [30–32].

Recently, the metamaterial absorber with various shapes for concentration of energy is noticed for sensor in the wide range from microwave [33] to infrared and optical range for bio-sensing applications [34]. In fact, the metamaterial gaps make capacitance which has effect on improvement of the electric field for sensing with more accuracy [35].

Based on previous researches on plasmonic absorber and possibility of designing hollow structure, in the current research we have modeled a hollow cylindered absorber in optical frequencies. In this paper we have described the proposed structure and presented parametric studies on the height and thickness of hollow cylinders. In addition, for a low and high Q factor model, we show the biological material effect on the absorber response and then the frequency shift is noticed as an FOM factor. On the other hand, we have shown that this structure is useful for energy harvesting and by performing several parametric studies; we have revealed how parameters would have effect on frequency. Furthermore, we have concluded that it might helpful for organizing this particle for higher frequencies for solar cell applications.

2. Absorber design

Fig. 1(a) shows the 3D view of our proposed absorber array that is designed based on plasmonic properties and Fig. 1(b) shows the geometry of each unit cell. The hollow cylindrical structures are implemented over the gold ground layer and are separated by Al_2O_3 spacer with refractive index of 1.92, and the Palik model is utilized to represent the gold layer. Each unit cells dimensions are 310×310 nm^2 and the height (h), radius (r) and thickness (t) of the hollow cylindrical are modified for two various frequencies at 138 and 168 THz by parametric studies. The height of hollow cylinder is assumed 100 nm with the radius of r=90 nm and thickness of t=20 nm for lower frequencies (first modification), however for the higher frequencies (second modification) they are set to 85 and 40 nm, respectively. CST Microwave studio has been utilized as a commercial full wave simulation software to obtain the absorber reflection properties, and the periodic boundary condition is applied for side walls i.e. in x and y directions PMC and PEC boundaries have been used and the open boundary is selected as a conventional Perfect Matched Layer (PML) to a height of λ/4 for 3D simulation along the Z direction. In addition, there are pre-assumed dimensions in Fig. 1(b) such as a=310 nm, h_g=60 nm, and h_s=10 nm.

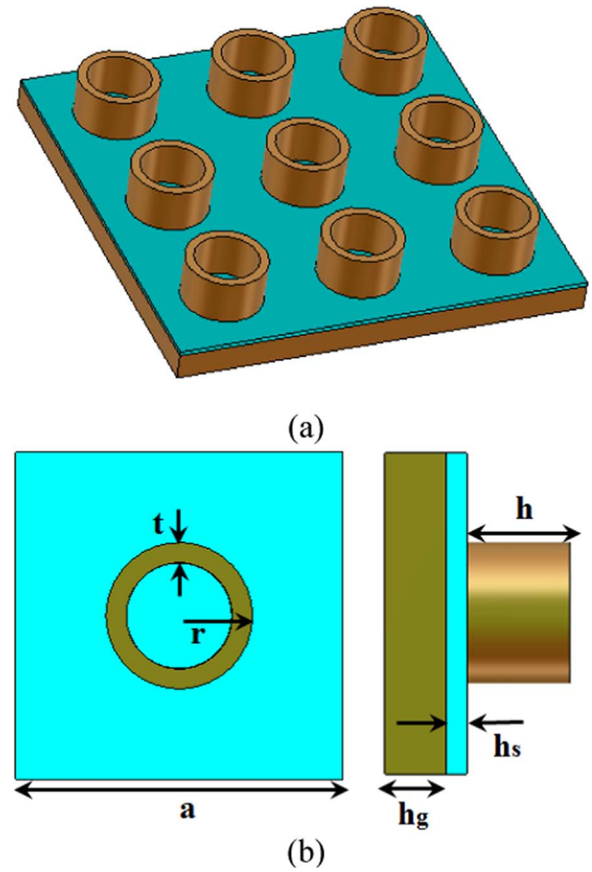

Fig. 1. The plasmonic absorber based on hollow cylinders (a) array formation (b) each unit cell.

3. Simulation result and discussions

As was described in the past section we have considered two cases those are t=20 nm for absorption at lower frequencies and t=40 nm for higher frequencies. Fig. 2 shows the result for the reflection (S_{11}) of the absorber for these two cases. In addition the thick gold layer as a ground has reduced the transmission (S_{21}) drastically and therefore it is around zero. Absorbance is defined by considering $A=1-R-T=1-|S_{21}|^2-|S_{11}|^2$ where S_{21} is known as the transmission amplitude and S_{11} is the reflection amplitude. Here S_{21} is around zero so we have $A=1-|S_{11}|^2$ [10]. The structure reflection has been studied with and without spacer at Fig. 2(a) and (b), respectively, with two various thicknesses of the cylinder. Exactly as it is shown in Fig. 2(b), in the absence of the spacer the frequency is shifted from Infrared to optical domain. As can be seen in here, by increasing the thickness of the cylinder, we have better control on the resonance shift. Fig. 2(a) shows the reflection with spacer layer and when the thickness of each cylinder increases from t=20 nm to t=40 nm the frequency of absorption would shift more than 30 THz from 135 to 165 THz and reflection value is reduced from 0.12 to 0.03, so the absorption quality is enhanced. Fig. 2(b) shows the reflection without any spacer layer and in this case the cylinder is connected to rectangular part. Performing simulation for t=20 nm, we saw that the resonance occurs at 425 THz with reflection value of the 0.3 and when the thickness is increased to 40 nm the frequency is shifted to 500 THz with reflection value of 0.15. Here the reflection amplitude is reduced a little by increasing the thickness and therefore the absorbance is improved.

Fig. 3(a) and (b) shows that by increasing the height of the cylinder, reflection decreases drastically and therefore absorption increases. In addition, the height of the cylindrical hollow effects the Q-factor of the structure where the Q-factor is intensified and resonances are shifted to higher frequencies (lower wavelengths). These variations in resonances are more visible in Fig. 3(a) when t=20 nm and there are more overall reflections between the cylindrical hollows. In this case, by changing the height from 60 nm to 100 nm, the reflection value is reduced around 0.4 with a frequency shift of 12 THz i.e. for h=60 nm the reflection value is around 0.5 at 124 THz. while by increasing h to 100 nm, the reflection is reduced to 0.12 at 136 THz. However, Fig. 3(b) shows that the resonance variation has smaller shift for t=40 nm when we have more absorption at higher frequencies by changing height from h=60 nm to 100nm in this structure, and the reflection values are reduced from 0.05 to 0.3 with a frequency shift around of 6 THz. Therefore with higher thicknesses we have less variation in reflection value and frequency shift, however we have more absorption in the case of higher thicknesses. As we had A=1-|