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Improvement of the bulk sensitivity and FoM of the plasmonic nanodipole antenna array

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Abstract

In this paper, the sensitivity of a plasmonic nanodipole antenna array for different materials of the metal nanodipole and substrate is calculated by changing the refractive index of the surrounding medium. The performance of our proposed array is studied at two wavelengths of 1310 and 1550 nm, the wavelengths of the second and third telecommunications windows. It is shown that by using the silver (Ag) nanodipole instead of the gold (Au) one, the bulk sensitivity of the nanostructure is improved. By replacing the substrate material from Si to SiO_2, the sensitivity increases up to 1220 and 1150 nm/RIU at the wavelengths of 1310 and 1550 nm, respectively, that is very suitable for sensing applications. Moreover, the figure of merit (FoM) of the plasmonic sensor is calculated for both substrates and nanodipole materials. The maximum value of the FoM is obtained for the nanoantenna array with SiO_2 substrate and Ag nanodipole and it is equal to 14.35. Furthermore, it is shown that by increasing the thickness of the nanodipole, the nanostructure sensitivity and FoM are enhanced.

Keywords: Figure of Merit (FoM), Nanoantenna, Optical Response, Sensitivity, Sensor.

1. Introduction

Nanoantennas are one of the important and applicable devices in the field of nanotechnology that have attracted many researchers' attentions due to their unique capabilities for sensing applications. Nanoparticle based sensors have been used for sensing applications so far. For example, the bulk sensitivity of about 71 nm/RIU has been reported by Okamoto et al. for the gold nanospheres mounted on the glass substrate [1]. Also, the bulk sensitivity of gold nanostructures with different shapes, including nanocylinders, nanodisks and nanoshells has been measured by Miller et al [2]. The sensitivities of 180 to 400 nm/RIU for nanocylinders with different height, 180 to 380 nm/RIU for nanodisks with different diameters, and 80 to 220 nm/RIU for nanoshells with different diameters have been obtained [2]. In Ref. [3] it has been shown that by increasing the height of nanorods, the sensitivity can be improved. The bulk sensitivities of nanorods with diameters of 20 and 40 nm and different heights have been reported about 153 to 495 nm/RIU and 245 to 645 nm/RIU, respectively. In Ref. [4], the bulk sensitivity of 153 nm/RIU has been obtained for the star-shaped nanostructure. By utilizing nanoantenna based sensors, in addition to high speed performance and subwavelength dimensions, a high efficiency can be achieved economically. The interaction of light with nanostructure causes some resonances based on the fluctuating electron accumulation at certain wavelengths that is called local surface plasmon resonance (LSPR) [5,6].

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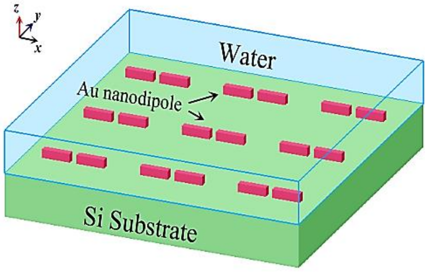
These resonances are equivalent to the sharp peaks in the absorption spectrum of the nanostructure. With any changes in the surrounding medium of the nanostructure, the resonance wavelength is shifted, and so design of nanosensor is based on these changes. The bulk sensitivity of the sensor that is the ratio of wavelength shift to the variation of the refractive index of the medium is given as follows [7]:

$$S = \frac{\Delta\lambda}{\Delta n} \tag{1}$$

This means that by any changes in the vicinity of the nanostructure, the resonance wavelength is altered. These changes can predict the possible events around the nanostructure. The structure material is one of the main factors that affect the performance of the nanosensor and is investigated in this article. We have shown that by choosing an appropriate material, the sensitivity of our proposed sensor based on the plasmonic nanodipole antenna array is improved.

2. Geometry

A schematic diagram of our proposed plasmonic nanodipole antennas array and its unit cell are shown in Fig. 1. This structure consists of three main parts: the substrate, the nanodipole, and the surrounding medium. The parameters of the structure are length (l), width (w), thickness (t) and gap of the nanodipole (g). The surrounding medium is chosen to be water that can be considered as an advantage in medical applications such as diagnosis of diseases from the saliva.



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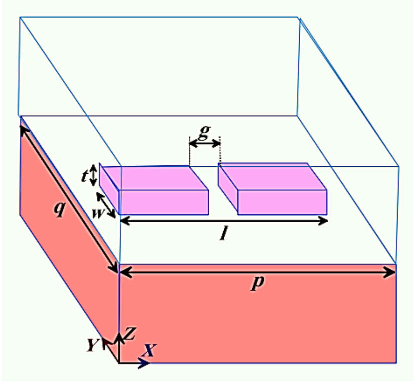

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Fig. 1: a) The schematic view of the proposed plasmonic nanodipole antennas array, and (b) the wide view of a unit cell of the array

In this paper, two different metals of silver (Ag) and gold (Au) are selected for nanodipole. Also, Silicon (Si) and Silica (SiO_2) materials are used for the substrate. An infinite array can be created by repeating the unit cell along the *x* and *y* directions with the pitch dimensions of *p* and *q*, respectively. The pitch size is 300 nm × 300 nm. All simulations are based on the finite-difference time-domain (FDTD) numerical method, with a 1 nm × 1 nm × 1 nm mesh in the region around the nanodipole. The array is illuminated by an *x*-polarized plane wave source that is embedded in the substrate and is 2.46 µm bellow the substrate-nanodipole interface. The refractive indices of gold and silver are chosen from Johnson and Christy’s model that some of these data at different wavelengths are depicted in Table. 1 [8]. Also, the refractive index of water at different wavelengths is extracted from Segelstein’s data [9].

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Wavelength (nm)	Silver	Gold
1215	0.09+j8.80	0.35+j8.20
1393	0.13+j10.1	0.43+j9.50
1610	0.15+j11.8	0.56+j11.2
1937	0.24+j14.1	0.92+j13.8

Table. 1. The refractive indices of gold and silver at some wavelengths based on Johnson and Christy's data [8]

3. Theory and Method

Surface plasmon resonances (SPPs) are the collective oscillations of electrons propagating through the metal-dielectric interfaces. These collective oscillations can be defined by the absorption power of the nanostructure that normally occurs at a specific wavelength. Therefore, the absorption spectrum is useful for computing the nanostructure sensitivity and can be expressed as [10]:

$$A = 1 - T - R \qquad (2)$$

where T and R are the transmission and reflection powers. In all simulations, the monitors for measuring the transmission and reflection spectra are located 2.5 μm above and below the substrate-nanodipole interface, respectively.

For calculating the nanostructure sensitivity, the refractive index of the surrounding medium at the resonance wavelength (λ_{res}), the wavelength that the value of the absorption spectrum is maximum, is extracted. When the refractive index of the surrounding medium is changed by the value of h_d, a resonance shift in the absorption spectrum occurrs. By measuring the value of the resonance shift, the bulk sensitivity can be achieved by approximating the differential via central finite difference formula [11]:

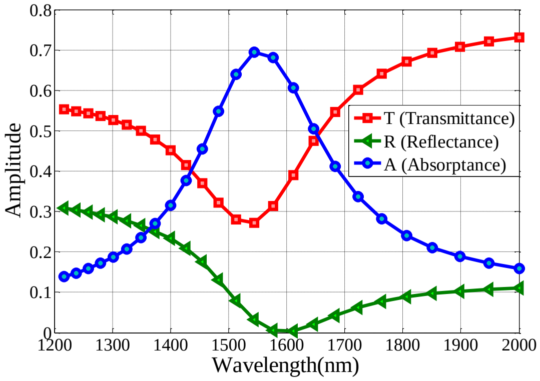
$$\frac{\partial \lambda_{res}}{\partial n_d} = \frac{\lambda_{res}(n_d + h_d) - \lambda_{res}(n_d - h_d)}{2h_d} \qquad (3)$$

where n_d is the refractive index of water at the resonance wavelength. In this approximation, the smaller h_d, leads to more accuracy in the sensitivity. In this article the value of h_d is assumed to be 0.005.

4. Simulation Results and Discussions

4.1. Optical Response

As mentioned, the absorption spectrum is used for calculating the bulk sensitivity. The optical response of a structure includes the transmission, the reflection, and the absorption spectra. The optical responses of a periodic array of gold and silver nanodipoles with the dimensions of $l = 230$nm, $w = 10$ nm, $t = 40$ nm, $g = 20$ nm and $p = q = 300$nm are shown in Fig. 2. It can be seen that the absorption spectrum of the silver nanodipole is much narrower than the gold one. This is because of the differences between the real and imaginary parts of the refractive indices of gold and silver at different wavelengths as depicted in Table. 1. Since the variation of the imaginary part of the refractive index of silver as a function of frequency is very slow compared to gold, the narrower and sharper absorption spectrum can be achieved that is appropriate for sensing applications.



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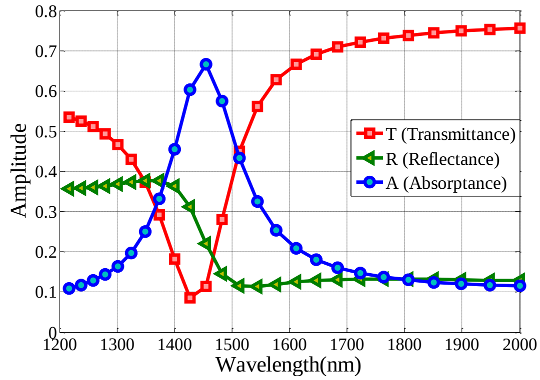

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Fig. 2. Transmission (line with square), reflection (line with triangle) and absorption (line with circle) of a periodic array of nanodipole antenna with a) gold and b) silver nanodipoles and the dimensions of $l = 230$ nm, $w = 10$ nm, $t = 40$ nm, $g = 20$ nm and $p = q = 300$ nm

4.2. Bulk Sensitivity

The resonance wavelength of the nanostructure depends on its geometry. By increasing the nanodipole length (l), the resonance wavelength shifts to the higher values [10]. In order to calculate the sensitivity at the resonance wavelengths of 1310 and 1550 nm, the wavelengths of the second and third telecommunication windows, the nanodipole dimensions are optimized according to the method of Ref. [12]. By changing the refractive index of the surrounding medium of about 0.005, the value of the wavelength shift is attained from the absorption spectrum and the sensitivity is calculated according to Eq. (3). The sensitivities of the periodic array of Fig. 1 versus the nanodipole thickness for gold and silver nanodipoles at 1310 and 1550 nm wavelengths are demonstrated in Fig. 3.

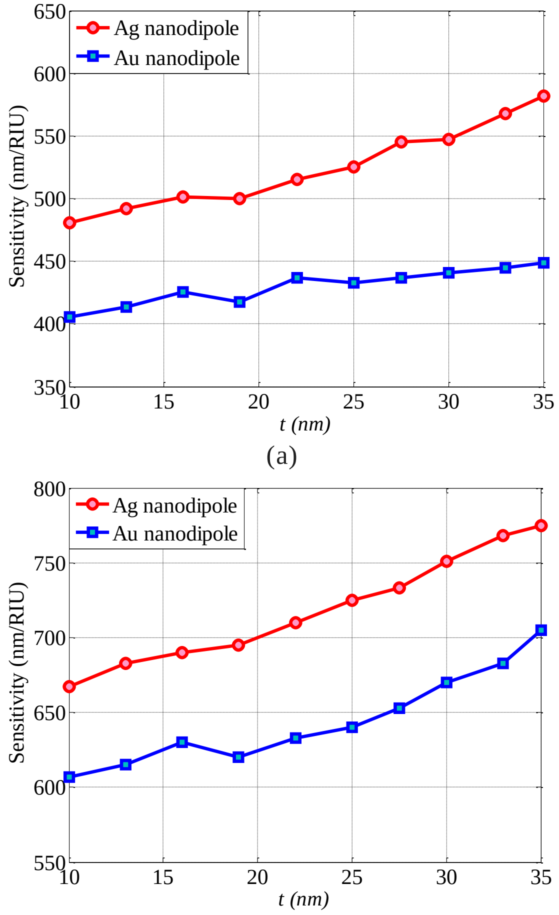

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Fig. 3. Sensitivity of the nanodipole array of Fig. 1 versus the nanodipole thickness (t) for Si substrate at a) 1310 nm and b) 1550 nm wavelengths

As expected, the nanosensor with silver nanodipole is more sensitive than the gold one. The maximum sensitivity is about 780 nm/RIU for silver nanodipole with the thickness of 35 nm at 1550 nm wavelength.

By replacing the substrate from Si with $n_{Si} = 3.5$ to SiO_2 with $n_{SiO_2} = 1.45$, the electromagnetic fields of the surface plasmon modes of nanodipole is changed and more overlapping at the sensing region occurs. Therefore, the sensitivity can be improved. The bulk sensitivity of our proposed array for SiO_2 substrate is depicted in Fig. 4. It is clear that the sensitivity is increased by a factor of about 2.2. The maximum sensitivity is obtained about 1220

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nm/RIU for silver nanodipole with the thickness of 35 nm at the wavelength of 1310 nm. The results show that by utilizing silver nanodipoles instead of gold ones, the higher sensitivity is obtained. Also, by using SiO_2 substrate, the sensitivity of the nanostructure is doubled that is a very high sensitivity for nanosensors. It is noteworthy that the obtained sensitivity is related to the small changes in the refractive index of the surrounding medium of about 0.005, which is a great advantage compared to the other nanosensors [1-4].

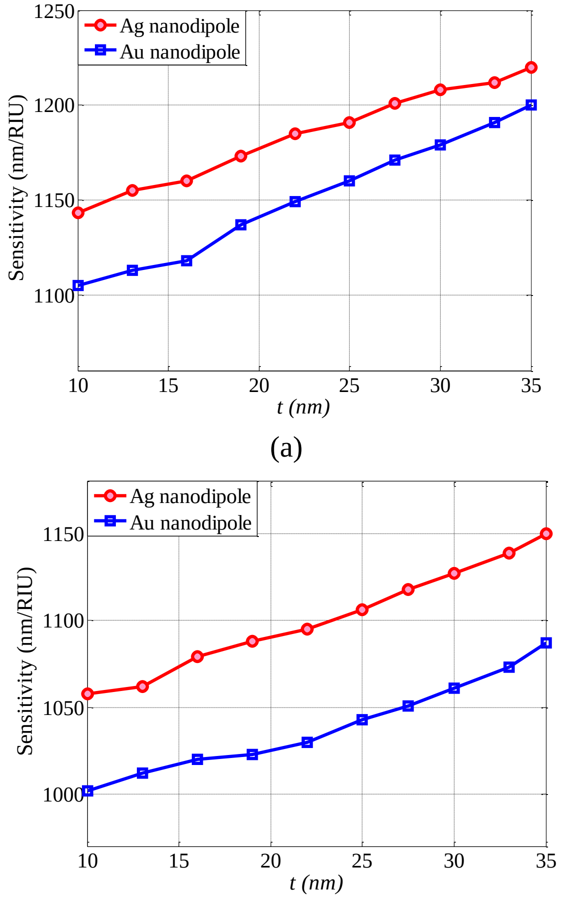

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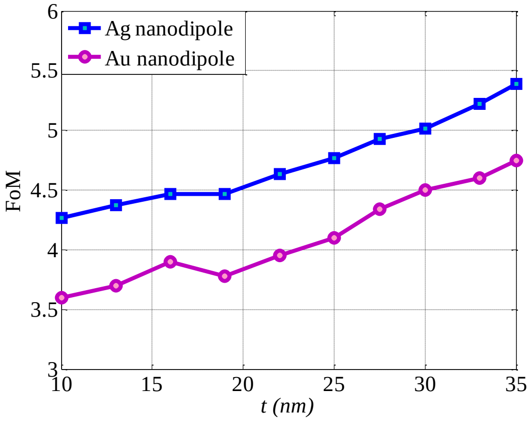
Fig. 4. Sensitivity of the nanodipole array of Fig. 1 versus the nanodipole thickness (*t*) for SiO_2 substrate at a) 1310 nm and b)1550 nm wavelengths

Furthermore, Figs. 3 and 4 demonstrate that by increasing the thickness of the nanodipole, the sensitivity is increased due to decreasing the effective refractive index of the structure.

Besides the sensitivity of the structure, the figure of merit (FoM) is an important factor for sensing applications that is defined as the sensitivity normalized by the resonance bandwidth. The resonance bandwidth is the difference between two wavelengths corresponding to the half value of the absorption curve. More FoM leads to better performance of the system.

The FoM of the plasmonic nanodipole antenna array with silver and gold nanodipoles on Si substrate at the resonance wavelengths of 1310 and 1550 nm for different nanodipole thicknesses is shown in Fig. 5. The bandwidth of the silver nanodipole array with the thickness of $t = 35$ nm at $\lambda_{res} = 1550$ nm is about 107.2 nm that leads to FoM=7.11. However, the bandwidth and FoM of the gold nanodipole array are 171 nm and 4.17, respectively. The bandwidth of the silver nanodipole array is narrower and its sensitivity is higher that the gold one. Therefore, the figure of merit of the proposed array with silver nanodipole is much higher that is suitable for sensing applications.



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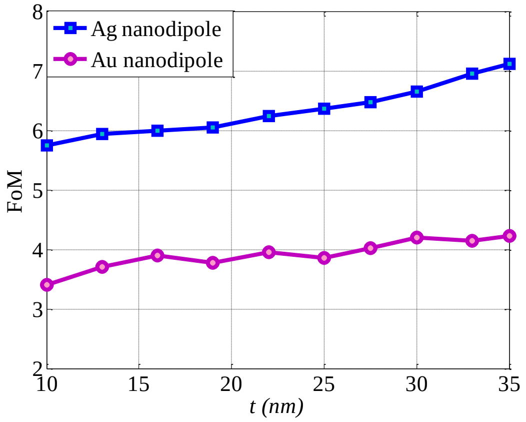

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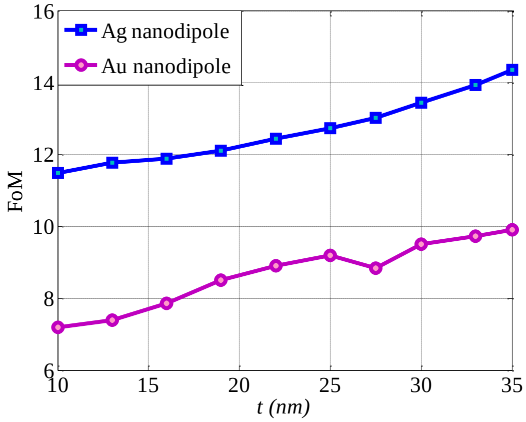
Fig. 5. Figure of merit of the nanodipole array of Fig. 1 versus the nanodipole thickness (*t*) for Si substrate at a) 1310 nm and b) 1550 nm wavelengths

The FoM of silver and gold nanodipole arrays on SiO_2 substrate at 1310 and 1550 nm wavelengths for different nanodipole thicknesses is depicted in Fig. 6.



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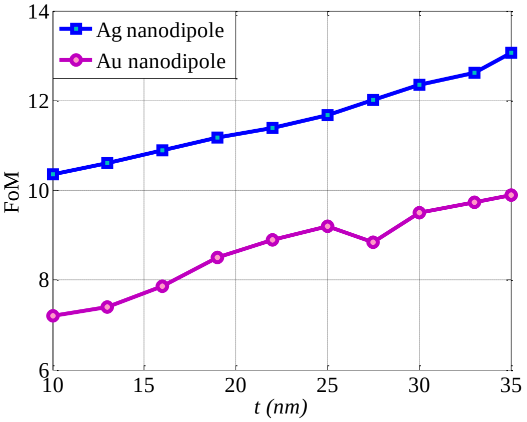

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Fig. 6. Figure of merit of the nanodipole array of Fig. 1 versus the nanodipole thickness (*t*) for SiO_2 substrate at a) 1310 nm and b) 1550 nm wavelengths

It is evident that by using SiO_2 substrate, the FoM of the nanostructure is enhanced due to improving the sensitivity. The bandwidth and FoM of our proposed nanoantenna array with SiO_2 substrate and the nanodipole thickness of $t = 35\ \text{nm}$ at $\lambda_{res} = 1310\ \text{nm}$ are 85 nm and 14.35, respectively.

5. Conclusion

In this paper, the sensitivity of a plasmonic nanodipole antenna array as a nanosensor has been calculated for different materials of nanodipole and substrate at the wavelengths of 1310 and 1550 nm. It has been shown that by utilizing silver nanodipole and SiO_2 substrate, the sensitivity of about 1220 nm/RIU has been attained at 1310 nm wavelength. Also, the maximum value of FoM for the plasmonic nanodipole antenna array with SiO_2 substrate and Ag nanodipole has been obtained to be 14.35. The results show that the proposed nanosensor with small changes in the refractive index of water as the surrounding medium is so useful for medical sensing and diagnosis of diseases from the saliva.

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