

# The nano loop antenna with Fano resonance and symmetrical formation and reconfigurable characteristic for bio-sensing application

Mohammad Vahedian<sup>1</sup> · Mohammad Naser-Moghadasi<sup>1</sup>

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**Abstract** The nanoantenna with Fano response is important for solar cell and bio-sensing application because of the more electric field enhancement. In this paper, we have presented a new structure based on two parallel nano loops and for achieving the Fano response; we have combined this structure with nano-sphere arrays which make a coupling between two nano loops. The Interaction between these nanoparticles is made bright and dark mode and Fano responses. To improve the electric field in this structure, we have implemented a multi-layer graphene under the nanoparticle. We show that by altering the chemical potential from 0.2 to 0.8 eV the maximum electric field has increased more than 20% for 0.6 eV in comparison to the case for 0.2 eV. We have studied the parameters effect on resonances. In addition, the presented antenna is used for biomaterial and we have compared the bare and coated structures which can consider as a figure of merit factor for optical sensing and imaging. Here, we have utilized the graphene layer with the thickness of 2 nm under the nanoparticle as multi-layer graphene. The structure is simulated based on the FIT method by the CST and for the substrate, we are selected SiO<sub>2</sub> with the thickness of 80 nm which is a normal substrate for graphene deposition and the Palik mode is considered for gold parts. As a result of the fact, the graphene can be considered for controlling the electric field and the optical nanoantenna for bio-sensing.

**Keywords** Plasmonic · Fano · Graphene · Distortion · Nanoantenna · Bio-sensing

## 1 Introduction

The progress in fabrication technology of micro and nanoscale devices has led to the new topic and characteristic which is resulted new devices in the optical range such as nanoantenna (Srivastava et al. 2017; Zarrabi et al. 2015). This new attribute is called

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✉ Mohammad Naser-Moghadasi  
mn.moghaddasi@srbiau.ac.ir

<sup>1</sup> Department of Electrical and Computer Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

Plasmonic which is made by joining metal with a dielectric lossless material in the optical frequency range (Polman 2008). Surface plasmons are optically induced oscillations of the free electrons at the surface of a metal (Srivastava et al. 2017; Zarrabi et al. 2015; Polman 2008; Zarrabi and Moghadasi 2017). Plasmonic phenomena are based on electronic excitations generated by an electromagnetic field that excites a metal/dielectric interface (Lim et al. 2017; Jahangiri et al. 2017). This propagation along the interface is known as a surface plasmon polaritons (SPP) (Nooshnab and Golmohammadi 2017) and its important part in various areas of science, such as optics, material science, biology and very recently in nano-electronics and nano-photonics (Dragoman and Dragoman 2008; Cala'Lesina et al. 2015). Surface plasmon polaritons (SPPs) have been noticed for energy enchantment in the near field in a subwavelength at optical regime (Zarrabi et al. 2017).

Furthermore, artificial sub-wavelength metamaterials, So they called metamaterials particle (Barnard et al. 2008; Wegener et al. 2008) and have gained great attention due its exotic properties in optic and photonics research (Mutlu et al. 2011) and have been used for various applications such as a resonator with the Fano response (Srivastava and Singh 2017).

Fano resonances are made by the interference between superradiant (bright mode) and subradiant (dark mode) modes and making extinction cross section with narrow band characteristic and asymmetric line shapes (Liu et al. 2016; Naser-Moghadasi et al. 2016).

Fano resonance with asymmetric shape is reported for various models such as quadrilaterals nano-antenna (Liu et al. 2016), SRR and rings (Naser-Moghadasi et al. 2016), anti-symmetric quadrumers (Ahmadivand and Pala 2015a), necklaces nano-disks clusters (Ahmadivand et al. 2015a) are noticed for biomedical and optical application (Cetin and Altug 2012).

On the other hand, metal nano-particle chains are studied on propagation optical excitations for making integrated optic devices with sizes in the range of tens nanometer and spheres are smaller than optical wavelengths based on dipolar resonance (Weber and Ford 2004) and nanospheres array have been developed for nanoantenna with a Fano scattering response as an optical switch (Hopkins et al. 2015). Furthermore, the heptamers structure with seven gold disks for bright and dark mode at Fano resonance have been studied (Alonso-Gonzalez et al. 2011).

However, a small distortion in nanoparticle will effect on extinction cross section and therefore in other previous research have been noticed to controllable nanoantenna resonance (Oubre and Nordlander 2004; Trügler et al. 2014).

Recently, graphene is introduced as a two-dimensional optical material which is contained only one carbon atom thick (Bavir and Fattah 2016), and get more attention because of its special optical and electrical properties (Schedin et al. 2010; Cox and Garcia de Abajo 2015). The graphene has been considered for electric field and resonance in nano-antenna (McLeod et al. 2014) and controlling the Fano resonance based on the interaction between gold and graphene for split ring resonator and bowtie structure (Zarrabi et al. 2016; Parvin et al. 2017).

In this paper, we have suggested new nanoantenna based on the combination of nanosphere and dual parallel loop structure. It resulted in a dual resonance response with Fano shape. The interaction between bright and dark mode is made Fano mode at Fano dip and the result shows that how the graphene chemical potential can be considered to improve the electric field in Fano dip more than 20%. In addition, the parametric structure is revealed that the structure formation is an important parameter for designing nanoantenna and achieving Fano response. The biomaterial affects resonances are checked and the FOM

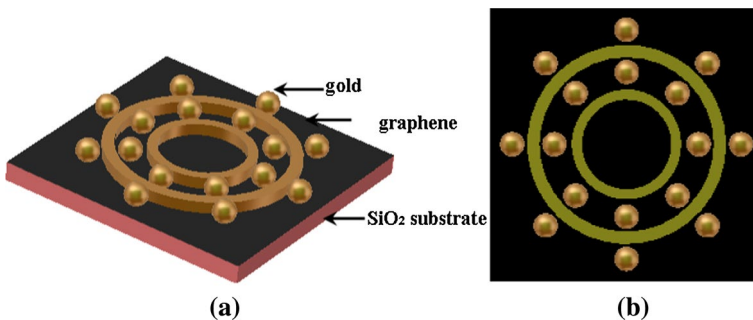
parameters are checked for various material. As shown in this paper, at the Fano dip, we have a linear shift for various refractive indexes.

## 2 Nanoparticle design

The combination loop and ring structure is presented as a nanoantenna with Fano response and the nanoantenna is placed over a  $\text{SiO}_2$  layer with refractive index of  $n=1.8$  that is selected as a substrate with the thickness of 78 nm which is suitable for graphene layer deposition (Riazimehr et al. 2017) and the Palik model is utilized for the gold parts in our structures (the rings and Nano-spheres). The Plane wave port is emitted the electric field with the power of 1 V/m in X direction and the CST microwave studio full wave simulator is utilized to do the simulation with time domain method (FIT) methods with open boundary and conventional PML is assumed for scattering cross section analyzing of the nanoantenna (Hadadi et al. 2016). The nanoantenna contains two coaxial loops with the width 40 and 50 nm for inner and outer loops respectively, and the inner radius of the inner loop is 180 nm and for the outer loop is 350 nm and the height of the nano loops for the final model assumed 50 nm. The two rows of the nanosphere are placed on two sides of the outer nano loop with a radius of 50 nm and eight spheres are placed in each row. Here, the gold layers are placed over the graphene (Fig. 1).

The Kubo formula performances are implemented in CST for graphene in these studies and graphene conductivity has two various terms of the  $\sigma_{\text{inter}}$  and  $\sigma_{\text{intra}}$  and therefore  $\sigma_G(\omega) = \sigma_{\text{inter}}(\omega) + \sigma_{\text{intra}}(\omega)$  (Hosseinbeig et al. 2017). To model the graphene, the temperature and relaxation time are 293 (K) and 0.7 (ps), respectively, and here the multilayer graphene has been considered with the thickness of 2 nm (Seyedsharbaty and Sadeghzadeh 2017).

The CST microwave studio<sup>®</sup> as a full wave commercial software is used which the Kubo equation is used for modeling the graphene layer and the surface conductivity  $\sigma_s$  of a single layer graphene can be modeled by Kubo conductivity and the photons by exciting the valance layer with interaction by conductivity layer are creating electron-cavity pairs and when the excitation occurs, the photon energy is transferred to the electron, The total loss of photon energy associated with the imaginary part and the dielectric coefficient or the actual part of the graphene conductivity coefficient (Hosseinbeig et al. 2017).



**Fig. 1** The geometry of the nanoantenna **a** the 3D view of the basic nanoantenna, **b** the view of the suggested nanoantenna

### 3 Simulation of the particle

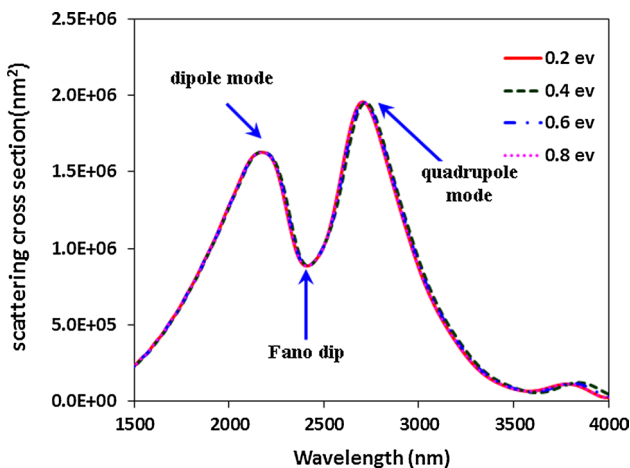
The plane wave is used for excitation of the nanoantenna and the scattering cross section is extracted for all structures. Also, the electric field enhancement for the final structure is checked by altering of the chemical potential. The electric field distribution is checked for bright and dark modes.

#### 3.1 The nanoantenna with various chemical potentials of graphene

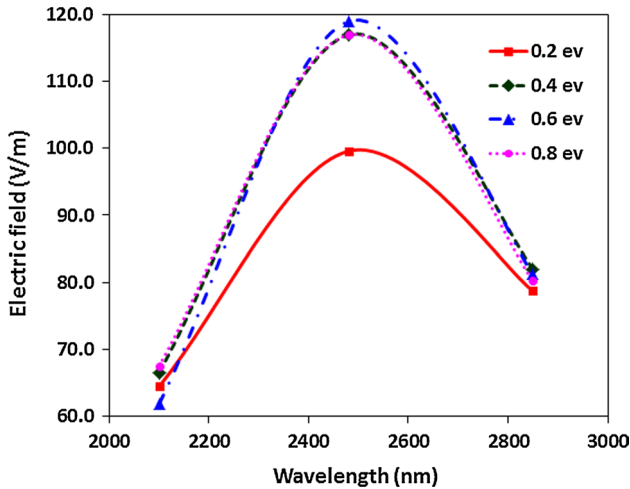
The nanoantenna with graphene layer is considered and the chemical potential is changed between 0.2 and 0.8 eV. The scattering cross-section (SCS) and the electric field enhancement are compared for various chemical potentials. Exactly, the chemical potential variation has less effect on the resonance frequency and it has caused a little frequency shift. Here, we have used the graphene as a dielectric layer and at this frequency, the permittivity of graphene has a few changes so it has not affect scattering cross section (SCS).

However, the tremendous variation of the electric field is visible. Figure 2 shows the scattering cross-section of the suggested structure for various chemical potentials in the range of the 0.2–0.8. As shown here, we have two resonances at  $\lambda_1=2100$  and  $\lambda_2=2850$  respectively, with SCS values of  $1.65 \text{ E}+06$  and  $1.9 \text{ E}+06 \text{ nm}^2$  for 0.2 eV and by increasing the chemical potential to 0.8 eV, we can see a little shift in SCS and small enhancement visible for SCS which is oriented from the high surface impedance of the graphene, however, we can neglect these changes. Furthermore, these chemical potential varieties show more effect on electric field enhancement and the results comparison are presented at Fig. 3 and, we show that with constant scattering cross-section, we can control the electric field.

Figure 3 shows comparison between the maximum of electric field enhancements of the nanoantenna at the surface of the interface of the metal and dielectric in the with various chemical potentials of the graphene layer as shows here by increasing the chemical potential from 0.2 to 0.8 eV the at Fano dip the electric field is increased up to 119 V/m for



**Fig. 2** The scattering cross-section of the presented nanoantenna with various chemical potentials of the graphene



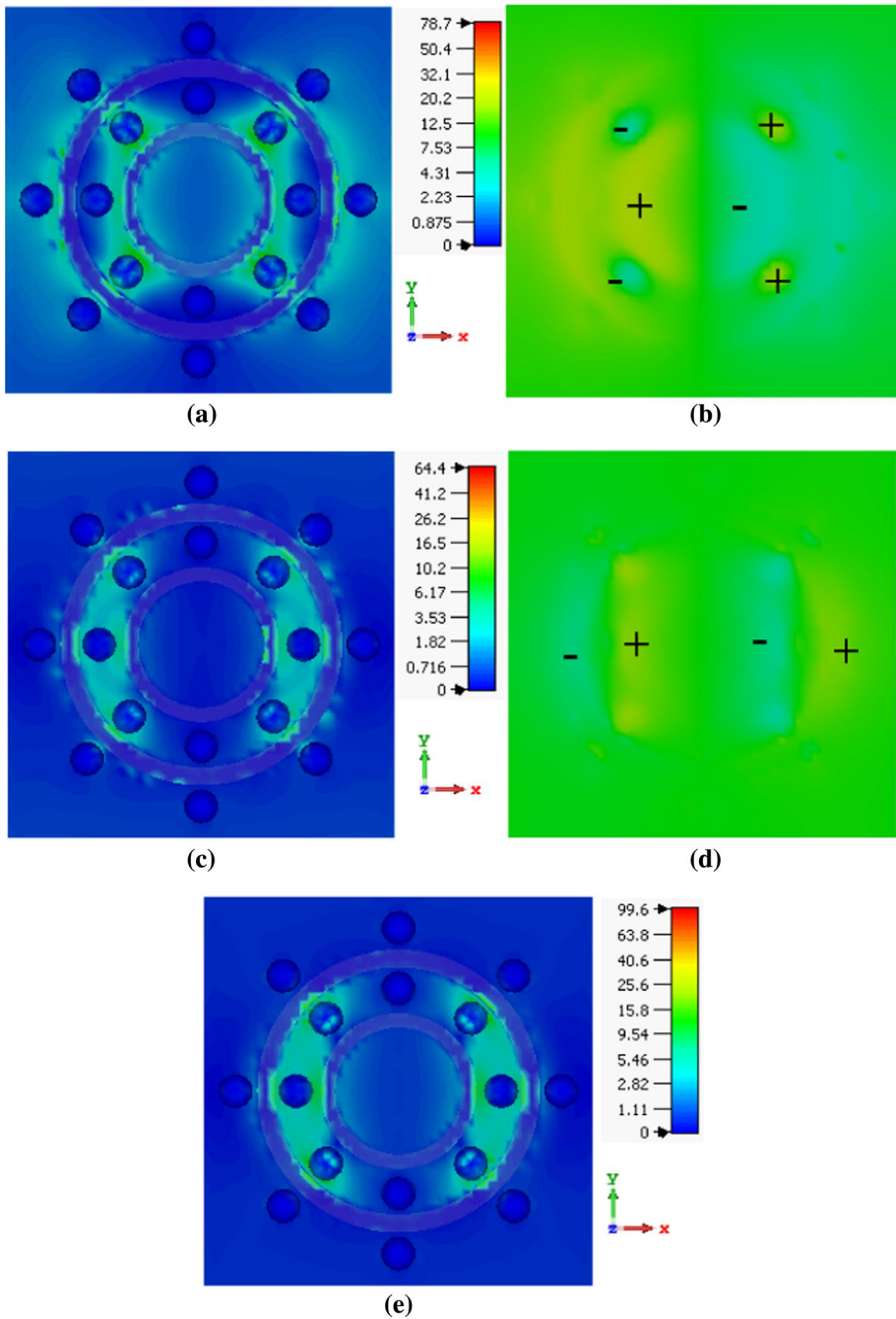
**Fig. 3** The electric field enhancement for dipole, quadrupole and Fano mode for various chemical potentials of the graphene

0.6 eV at 2480 nm, while the electric field is 99.6 V/m for the 0.2 eV. However, for 0.8 eV the electric field is decreased to 117 V/m and it's oriented from the nonlinear characteristic of the graphene and its interaction with surface plasmon. As shown here, we have plotted the Fig. 3 based on the maximum electric field at three points for the dipole, Fano and quadrupole at 2100, 2480 and 2850 nm respectively.

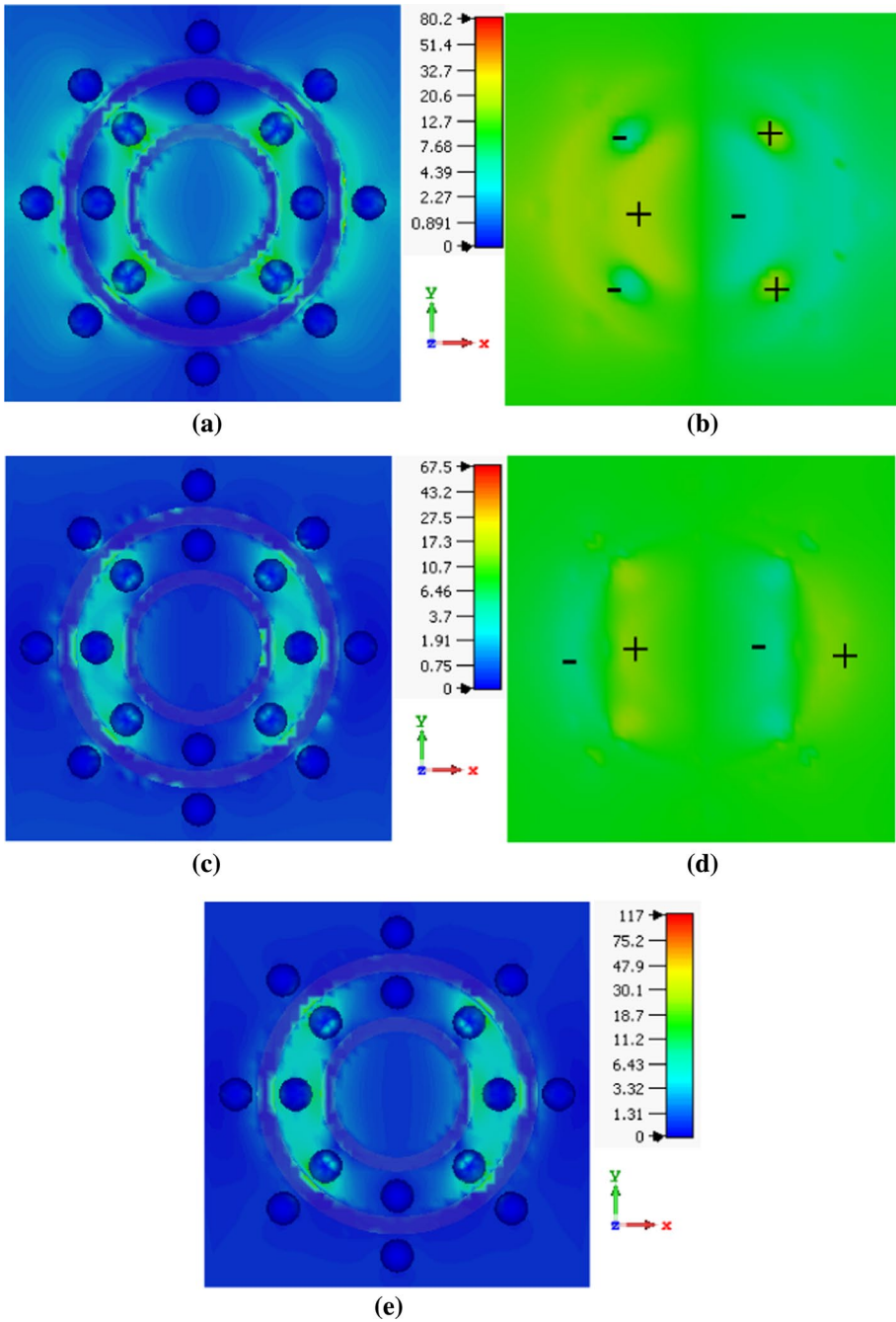
Figures 4 and 5 present the electric field enhancement of the chemical potential value of 0.2 and 0.8 eV. As shown in Figs. 4a and 5a at 2850 nm, the nanoantenna shows the quadrupole characteristic where the maximum electric field is placed at corners and Figs. 4c and 5c show the electric field for dipole mode at 2100 nm. The quadrupole is the sub-radiant mode and so it has more energy enhancement than the superradiant mode. Other electric fields are presented at Figs. 4e and 5e which has more energy which is made by the interaction of the dipole and quadrupole modes as it is occurring at 2480 nm which is known as Fano dip mode (Ahmadvand et al. 2015b). As shown in Fig. 3 by increasing the graphene chemical potential to 0.8 eV the energy increased, but the electric field distribution didn't change. In addition, we should consider that at Fano dip, the electric field distribution shape is the average of the quadrupole and dipole mode. In most cases, the dipole mode is placed at the higher wavelength. However, in some references models as mentioned by Ahmadvand et al. (2015a) and Ahmadvand and Pala (2015b) the different attributes have been seen. In addition, we should consider that we have a coupling between two sphere layer and we have two dipoles and this especial formation caused this opposite characteristic and this situation is shown at Figs. 4 and 5.

### 3.2 The parametric studies of the nanoparticle

The physical variation can affect the nanoantenna SCS and as our results show that by these variations, the Fano resonance can convert to plasmonic resonances which are not attractive for us and here we have checked three main parameter effect on SCS of the nanoantenna.



**Fig. 4** Electric field distribution for proposed nano-antenna for chemical potential of 0.2 eV **a** for quadrupole mode at 2850 nm, **b** the charge distribution for quadrupole mode at 2850 nm, **c** for dipole mode at 2100 nm, **d** the charge distribution for dipole mode at 2100 nm, **e** for Fano mode at 2480 nm



**Fig. 5** Electric field distribution for proposed nano-antenna for chemical potential of 0.8 eV **a** for quadrupole mode at 2850 nm, **b** the charge distribution for quadrupole mode at 2850 nm, **c** for dipole mode at 2100 nm, **d** the charge distribution for dipole mode at 2100 nm, **e** for Fano mode at 2480 nm



### 3.2.1 The central nano loops radius effect on scattering

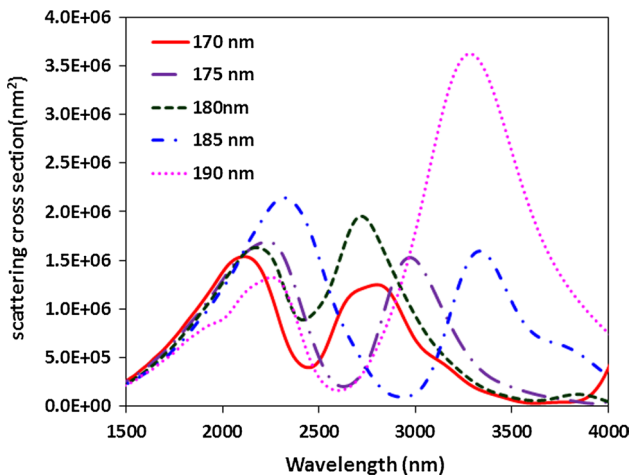
The first parameter is the radius of the central loop and as shown in Fig. 6 by changes in the inner radius with the constant width, the SCS is changed with the nonlinear formation. For example, by increasing and decreasing the radius to 185 and 175 nm, the distances between resonances are increased while for 170 nm these resonances are near together. On the other hand, by altering the radius, the Fano shape is changed to dual dipole resonances.

### 3.2.2 The thickness of the inner and outer loop effect on scattering

Figure 7 shows the second parametric studies that the thickness of the nano loops is checked and we can realize by Fig. 8 that the thicker ring is improved the plasmonic localization and reduced the nanosphere effect. As shown here, for 60 and 70 nm, the dual-band and Fano shape is eliminated and dipole formation is visible at 2500 nm with SCS of the  $2.3 \text{ E}+06$ . On the other hand, the thickness, reducing is not suitable too, while we can see two dipole resonances at 2250 and 3300 nm and coupling between nanoparticle and hybridization are neutralized. Therefore, the best result is achieved for the thickness of the 50 nm.

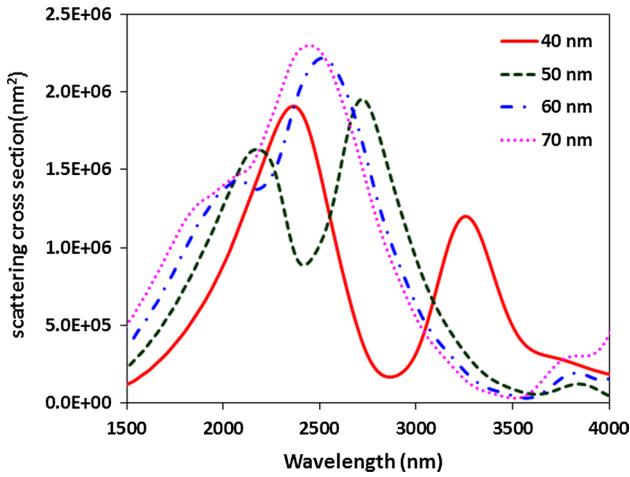
### 3.2.3 The nanosphere radius effect on scattering

Figure 8 shows the last parametric studies over the nanospheres radius and the results shows that the effect of the nanosphere radius the same as the nano loops thickness effect on SCS. As shown here, for 55 and 60 nm, the dual-band and Fano shape is eliminated again and dipole formation is visible at 2600 nm with SCS of the  $3 \text{ E}+06$  and radius reducing is not useful while the Fano response doesn't achieve.

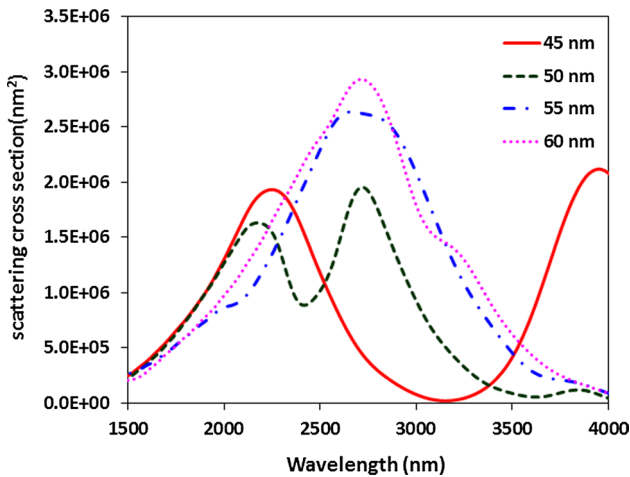


**Fig. 6** The scattering cross-section of the presented nanoantenna for various radius of the inner nano loop





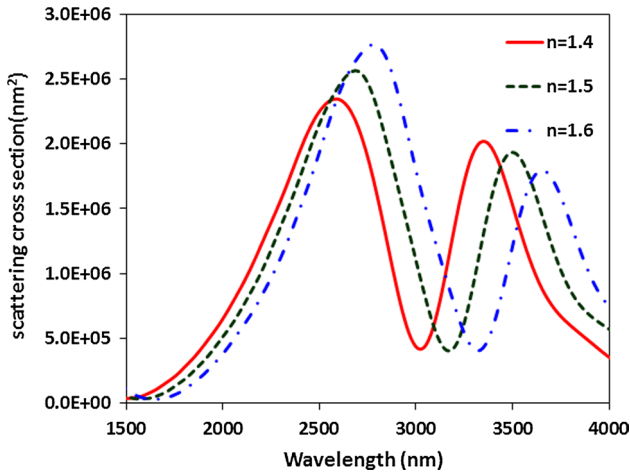
**Fig. 7** The scattering cross-section of the presented nanoantenna for various thickness of the nano loops



**Fig. 8** The scattering cross-section of the presented nanoantenna for various radiuses of the nanospheres

### 3.3 The external material effect on the nanoantenna scattering

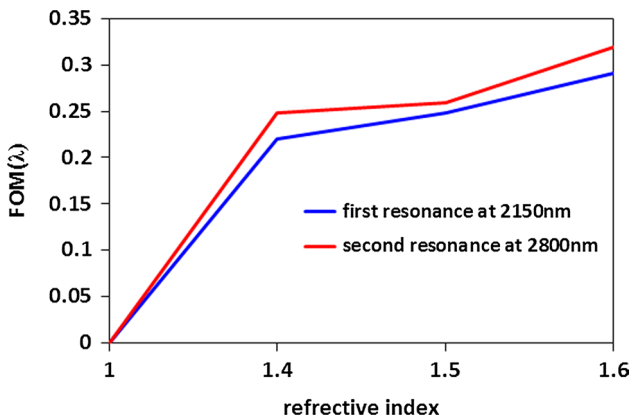
The external materials such as gens and antibodies have been recognized by the effect of them on the reflection or cross sections (Cetin et al. 2015). In Cetin et al. (2015) the model for protein A/G permittivity around 2.2 and here we have assumed three materials with the refractive index of 1.4, 1.5 and 1.6 as an external material and we have checked for the chemical potential of 0.2 eV and the results are presented at Fig. 9. As shows here, by increasing the refractive index the resonances are shifted to higher wavelength, but we should notice few points about the quadrupole and dipole resonances and Fano dip. At first, we should mention that the scattering cross section is increased up to  $2.8 \text{ E}+06$  when the external material is placed with the thickness of 100 nm over the nanoantenna. Another point is the variation in quadrupole and dipole mode while the



**Fig. 9** The scattering cross-section of the presented nanoantenna for various materials for graphene with chemical potential of 0.2 and 0.8 eV

RCS is increased for dipole mode and is decreased at the quadrupole mode by increasing the refractive index of the external material. At the final and the main point is about the Fano dip and as shown here, the Fano dips are shown constant scattering cross section and changes occur with linear variations. We can obtain the FOM factor by dividing the resonance peak variation wavelength ( $\Delta\lambda$ ) on the resonance peak wavelength ( $\lambda_0$ ) in the absences of additional material (Zarrabi and Naser-Moghadasi 2017; Ahmadivand and Pala 2015b).

The FOM of the prototype nanoantenna is presented at Fig. 10 and as shown here, by increasing the refractive index of the FOM is increased and in addition, the dark mode at 2800 nm shows better FOM than the bright mode at 2100 nm.



**Fig. 10** The FOM of the nanoantenna for various refractive index for dipole (2100 nm) and quadrupole (2800 nm)

## 4 Conclusion

The nanoantenna based on making the coupling between two nano loops was modeled while the nanoantenna was placed on the graphene layer. The antenna shows Fano mode with higher electric field enhancement, which is made by the interaction between the dipole and quadrupole and as the main result we show that by increasing the chemical potential of the graphene layer we able achieve higher electric field enhancement typically. This nanoantenna is used for bio-sensing and results are compared for the chemical potential of 0.2. The Fano dips are shown constant scattering cross section and changes occur with linear variations which are important for nanosensors.

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