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Developing the Plasmonic Fractal Nanoantenna for Energy Harvesting and Biosensing Application

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Abstract

In this paper, a Plasmonic arc-shaped nanoantenna is modeled and developed for light trapping and energy enhancement with the multi-Fano response for the mid-infrared spectra in the range of 2000-6000 μm. A symmetric model is suggested to achieve Fano line-shapes and make a hot spot to increase the electric field intensity. Fano response is gained by adding inner parasitic arc elements to the primary Plasmonic ring antenna. Then, the triple jounced ring structure is utilized to improve the electric field intensity. The final nanoantenna depicts that we can improve the electric field with this current nanoantenna with multi-Fano characteristics in comparison to the single Fano response. The maximum electric field efficiency is obtained 450 times which shows more than 300% enhancement in comparison to a simple ring nanoantenna. The efficiency of 650 times obtained with slant polarization. The sensitivity of the external biological material is checked for the single and multi-Fano elements. The maximum value of sensitivity for the final nanoantenna is 1458 nm/RIU. The multi-Fano has advantages for trapping energy in wider bandwidth and limiting the energy losses in the Plasmonic and Fano resonance.

Keywords: Biosensing, Energy harvesting, Fano, Heptamers, Plasmonic.

1. INTRODUCTION

The interactions of the metal and dielectric surface in the optical spectrum in the recent research works have led to discovering novel nanoscale metal structures called Plasmonic nanostructures [1].

The surface Plasmon Polaritons (SPPs) are made by oscillations of free electrons on the surface boundary of metal and dielectric [2]. Based on the Drude equation, it made

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negative permittivity for metal by $\varepsilon_m = \varepsilon_\infty - \omega_p^2/(\omega^2 + i\omega\gamma)$ where ω_p is the plasma frequency, ε_∞ is the relative permittivity at the infinite frequency, ω is the operating frequency of incident light and γ is the collision frequency [3-4]. Light interaction with metal free-electrons led to a collection of oscillating surface electrons which provides high absorption and scattering of the incident photon from the surface of the metal [3-4]. This behavior of metal in the optical spectrum has been noticed in various research during the last decade which is based on the re-radiative characteristic, for various devices such as super-lenses [5], Fano-like resonances in nanoparticle clusters [6], broadband light bending with nanoantenna [7], tunable directional coupling with polarization controlling [8], and mid-infrared Plasmonic bio-sensing with graphene [9].

Therefore, for designing the nanoantennas with the Fano line shape, various models have been suggested in the asymmetric and symmetric formations. Plasmonic Heptamers is a conventional form for Fano resonance [10], and recently more studies have been done over this arrangement for Fano switches [11], Plasmonic necklaces composed of gold nanodisks [12-13], and multiple Fano polarization independent resonances [14]. The asymmetric models are conventional for arousing the Fano response such as the Moon model for squeezing the magnetic field in the infrared region [15], Fano resonance ring/disk Plasmonic for bio-sensing [16], rod coupled Plasmonic systems [17], split concentric nano-ring resonator dimmers [18], and hotspots in a single-stone ring-like structure [19]. The external material impacts different parameters of the nanoantenna such as extinction cross-section and it can make a red-shift which is noticed for optical spectroscopy or Surface-Enhanced Raman Spectroscopy (SERS) and we can obtain the sensitivity factor based on the frequency shift [20].

The geometrical shape which is made by self-similar elements is called fractal, and various shapes in nature, such as galaxies, cloud boundaries, mountain ranges, coastlines, snowflakes, trees, leaves, ferns, and much more samples exist with this role [21]. In the optical spectrum for multi-resonance application and field enhancement, the fractal structures are being noticed tremendously [22-24].

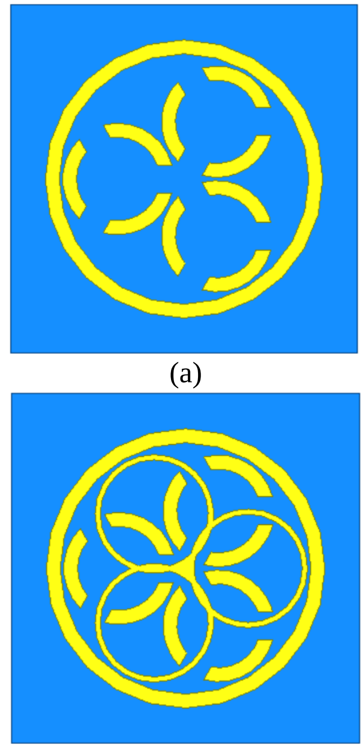
In this paper, we have investigated a novel nanoantenna with the multi-Fano response. We suggest a special form of a fractal ring. The external nanoparticle effects on the nanoantennas are studied for various materials to extract the sensitivity. Furthermore, the symmetrical structure is applied for the independency of the polarization to the incident wave. Fano resonance improves the energy summit at the dark mode more than 1100 % while for the first model the $|E^2|/|E_{int}^2|$ is around 14400 and for the final model, this ratio is increased up to 164000. In brief, for the bright mode, we have more than 300% enhancement in comparison to the simple model. In other words, it has increased from 14400 to 31600. As the main result, we show that the final nanoantenna is useful for trapping energy in wider bandwidth and saving energy in a constant state.

2. NANOANTENNA DESIGN

In this paper, a prototype of nanoantenna based on ring nanoantennas with inner arc fractal form is presented, which has been debated in our previous research by a split-ring resonator for the multi Fano [25]. Fig.1 (a) and Fig.1 (b) illustrate an oligomer model for Fano and modified model. The outer and inner radiuses of the bigger ring are 400 and 360 nm, respectively, and the metal thickness is assumed to be 40 nm and the location of this bigger ring is as same as the previous research [25]. We have implemented three small rings with outer and inner radiuses of 160 and 120 nm, respectively, with a similar metal thickness. There are 50 nm gaps in the smaller rings. The Palik model is used for the gold layer in the optical spectrum, and the Si_3N_4 composite layer is used as a substrate with n=1.98 (refractive index of 1.98) as kind of silicon crystals, the total dimensions are selected as 1000×1000 nm^2 and a thickness of 80 nm for the substrate is assumed. In the final antenna, three more rings with a narrower track width of 20 nm (Fig. 1(b)) are added. Exactly, the distortion of the fabrication in gaps of the ring structure is a big challenge for this structure. However, the gaps with small dimensions have been reported in some research [26] and here in this model, we are supposed to modify the gaps between the outer ring and jointed ring 10nm.

3. SIMULATION AND DESIGN

The incident electric field is directed in the X direction and with an intensity of 1V/m also CST microwave studio has been used for



(a)

(b)

Fig. 1. Top view of Fano resonance antenna prototype (a) Fractal antenna with Fano resonance (b) Modified nanoantenna.

carrying out the full-wave simulations based on the FIT method (Finite Integration Technique) as the time-domain method. The plane wave is used for excitation of the TEM mode for nanoparticle.

The boundary condition is assumed with an open space boundary for all sides with hexahedral mesh. Here, the extinction cross-section is obtained for the prototype nanoantenna by gathering the absorption and reflection cross-section based on Mie theory in the Plasmonic surface [27]. In Fig.2 the extinction cross-section is in nm^2 for both two presented models of Fig.1 and it is compared with a simple nano ring antenna in mid-infrared wavelength at the range of 2000-6000 nm. The simple ring nanoantenna has a Plasmonic resonance at λ_1=4100 nm with the maximum extinction cross-section around 5.46E+06 nm^2. The fractal nanoantenna has two resonances which emerged at λ_1=3300 nm and λ_2=4400 nm and the maximum extinction cross-sections are about 1.25E+06 nm^2 and 5.26E+06 nm^2, respectively. In the final nanoantenna with a Fano mode, we observe three resonances at λ_1=3000 nm, λ_2=3400 nm, and λ_3=4600 nm which are comparable with each other and the maximum extinction cross-sections are near, 2.25E+06 nm^2, 3E+06 nm^2, and 2.8E+06 nm^2, respectively.

Fig.3 shows the electric field distribution for the simple ring, fractal and final nanoantennas at their resonance frequency. For the first structure, we have a resonance at 4100 nm with $|E^2|/|E_{int}^2|$of 15876 where the E_{int} is known as an internal electrical field for incident wave. On the other hand, in the first Fano structure (fractal antenna in Fig. 1(a)), we have two resonances at 4400 and 3300 nm which is shown in Figs. 3 (b) and (c), respectively. In addition, the first resonance at 4400 nm shows the bright mode with lower energy and for the latter at 3300 nm, the dark mode has occurred with much higher energy. The second prototype of the nanoantennas is shown in Fig.1 (b). We have the Fano characteristic with one bright mode at 4550 nm and two dark modes at 3600 nm and 2800 nm. Fig. 3(d) and (f) show the electric field density at these resonant modes. Fano resonance can enhance the Energy summit at the dark mode more than 1100 %. Also, for bright mode, we have more than 300% enhancement for the electric field.

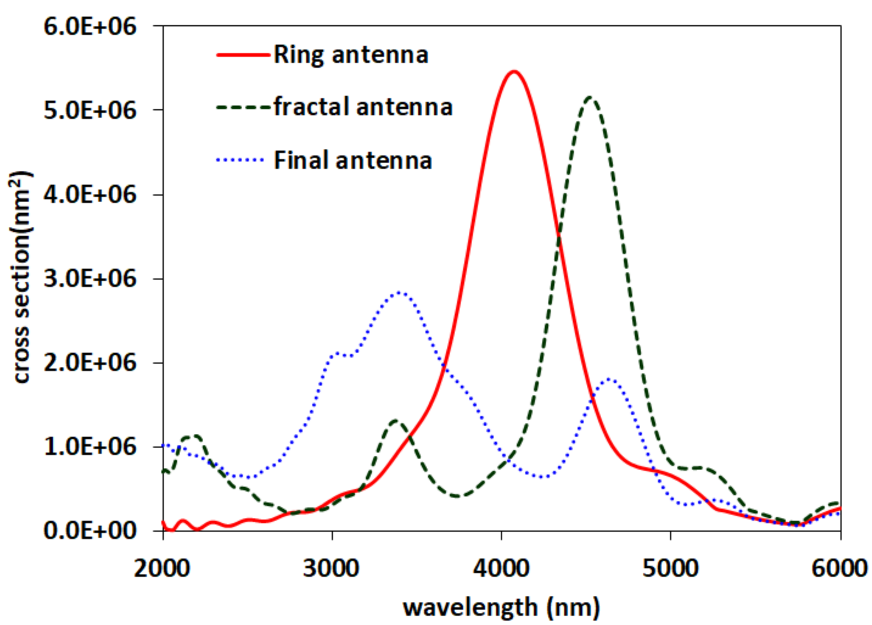


Fig. 2. The extinction cross-section for three studied structures in the range of 2000-6000nm.

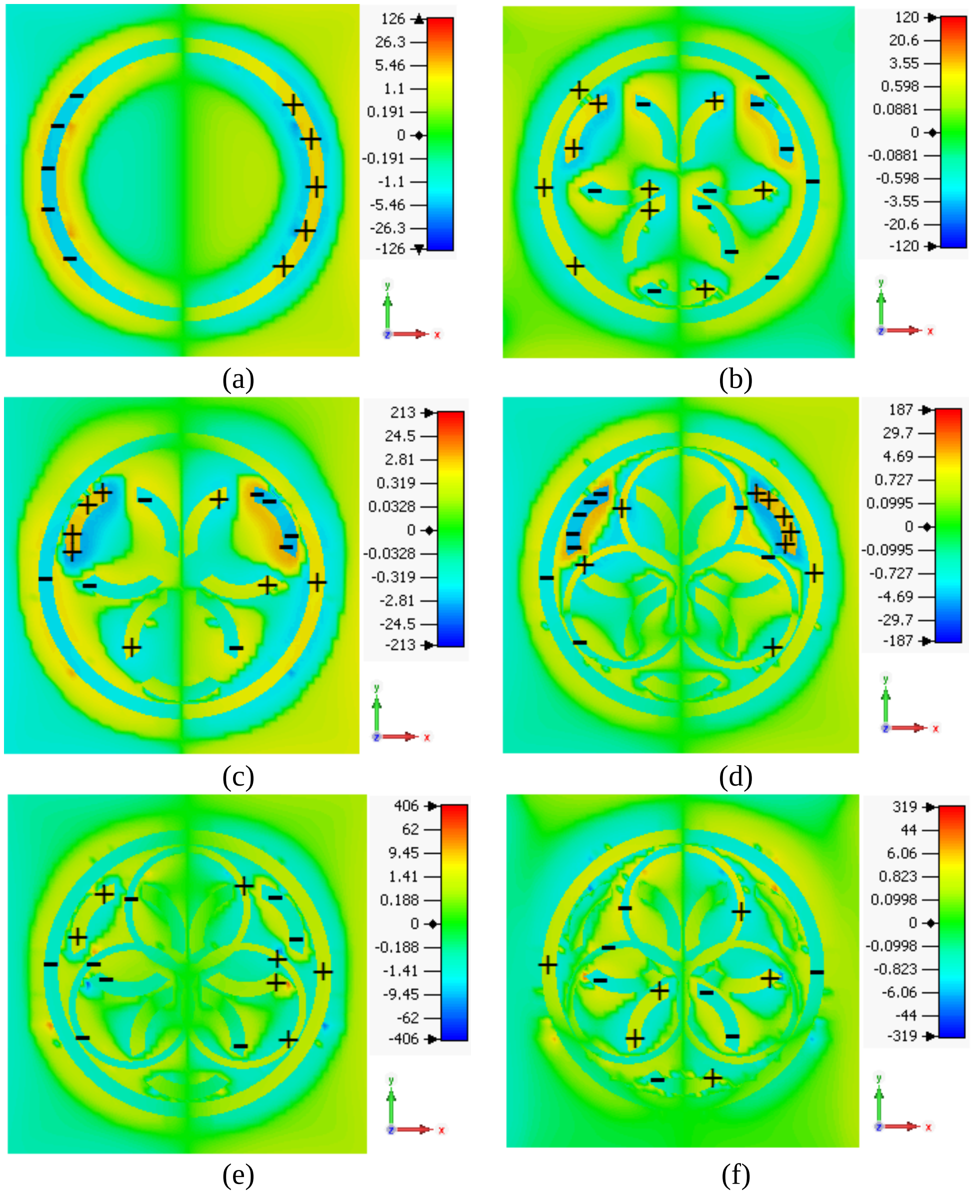


Fig.3. E-Field distribution of the nanoantennas (a) Dipole mode for nano-ring at 4100 nm (b) bright mode for fractal nanoantenna at 4400 nm (c) dark mode for fractal antenna at 3300 nm(d) bright mode for final nanoantenna at 4550 nm (e) dark mode for final nanoantenna at 3600 nm (f) dark mode for final nanoantenna at 2800 nm.

As shown here, we have dipole mode for the Nano ring antenna (Fig.3 (a)). When the split rings are added to the nanoantenna, dipole mode is visible for 4400 nm while the charge is placed in a symmetrical formation (Fig.3 (b)). In the second resonance at 3300 nm, the dark mode appears and the field is concentrated at two points (Fig.3 (c)). For the final nanoantenna, the field distribution is changed when the inner fractal ring is utilized. The gap widths are reduced and so the hot spots are limited at some points. In fact, it results in a higher energy enhancement at 3600 nm (Fig.3 (e)) and the bright mode happens at 4550nm (Fig.3 (d)).

As we mentioned, the incident wave field is 1V/m and efficiency mean how much the electric field enhances at the surface of metal-dielectric.

The E-field (electric field) efficiency is given in Fig.4 and for three cases has been studied in the range of 2000 to 6000 nm. In this research, we have found an interesting phenomenon for the final structure (modified Fano nanoantenna) in comparison with the conventional and Plasmonic fractal nanoantennas. In the fractal nanoantenna, the maximum efficiency is much lower than the Fano model. Therefore, if we assume this particle as a part of the solar cell, the active part of the solar cell accepts less energy, and it would not be used for energy harvesting. To overcome this problem, Fano resonances in nanoantennas are suggested. According to Fig.4, for the second structure, the area under the curve is increased in comparison with the simple ring nanoantenna, which is a factor of receiving energy. However, in Fano structure, the efficiency is reduced around the dark mode, and it leads to reduction of the solar cell efficiency. Therefore, we look for a way to save the energy at a constant state that provides wider bandwidth for the solar cells for light trapping.

For this aim, the multi-Fano nanoantenna is suggested as it is presented in Fig.2; the extinction cross-section of this nanoantenna has three peaks. In Fig.4, the efficiency diagram shows this nanoantenna has two dark modes between 3000-4000 nm. However, these dark modes make one peak in the cross-section.

Occurring two dark modes in final structure has made a special hot area in the range of 2800-3600 nm where the efficiency is typically more than 300 V/m. the second dark mode limits the efficiency reduction after the first dark mode resonance. Thus this characteristic provides wider bandwidth with high efficiency.

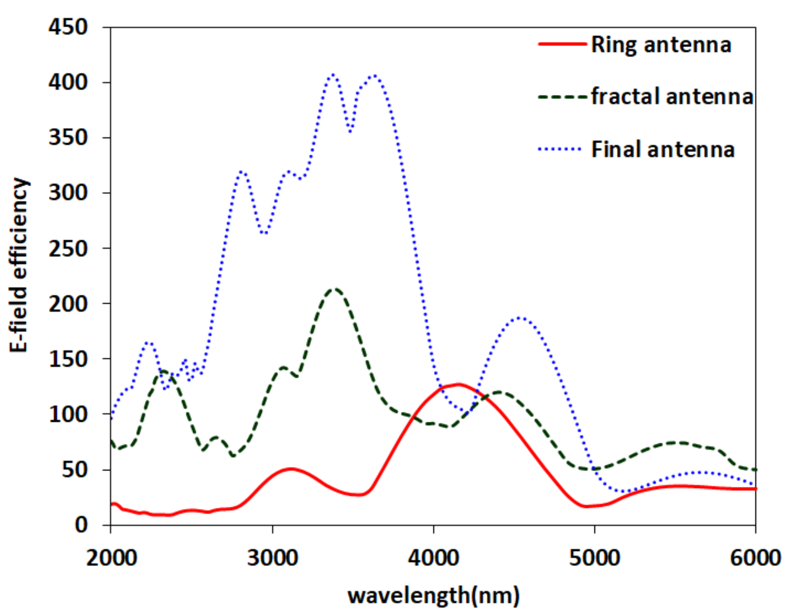
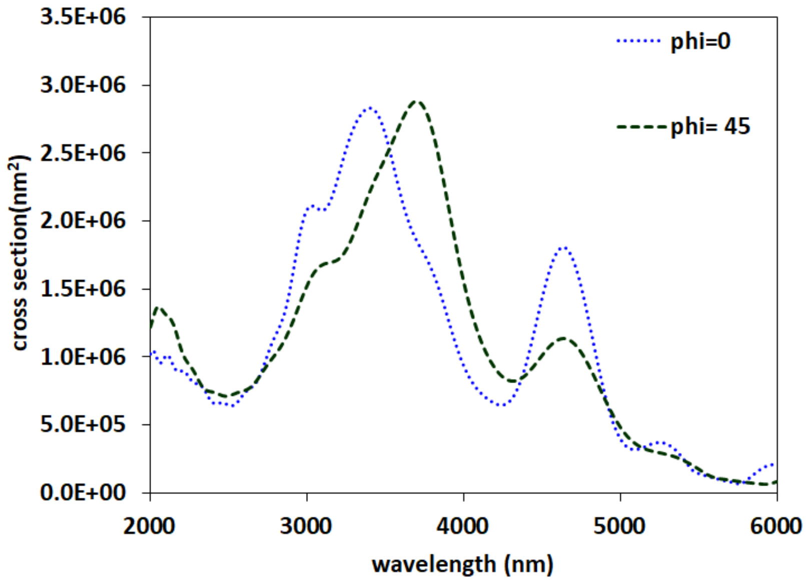
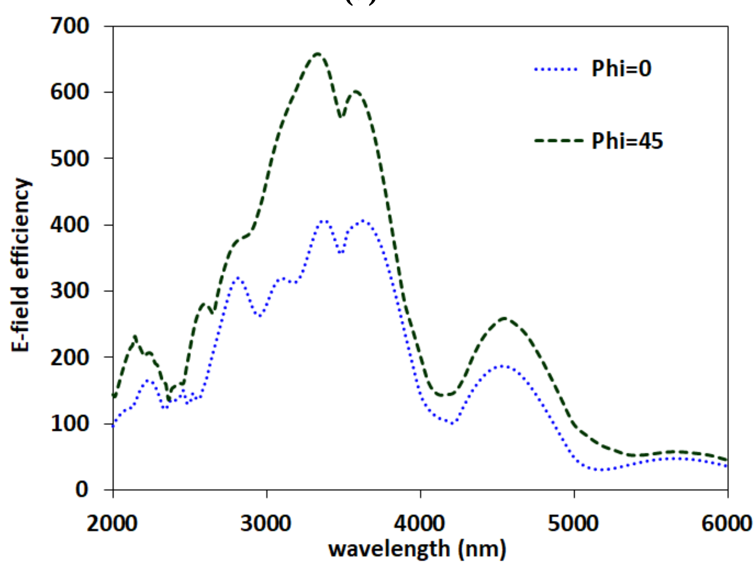


Fig. 4. The E-field efficiency studied for all three structures.



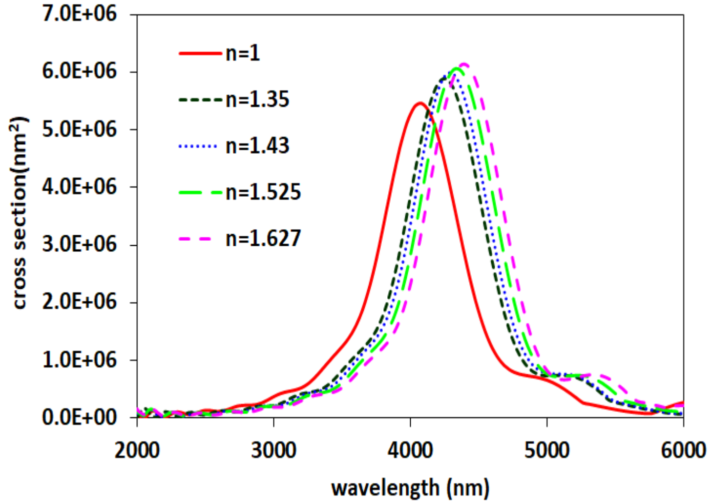
(a)



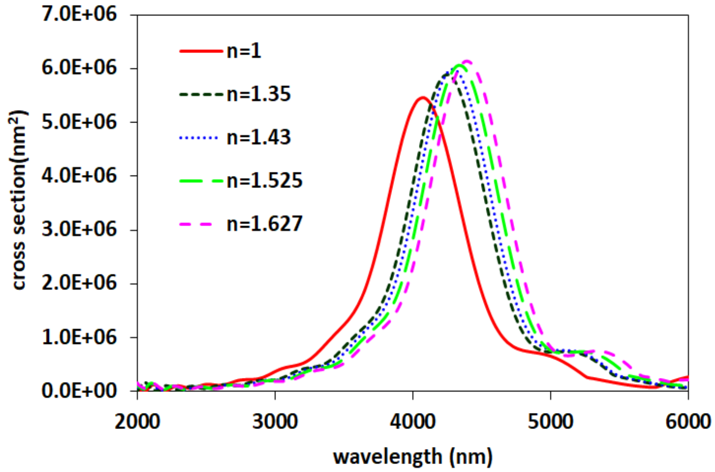
(b)

Fig. 5. The incident wave polarization angle effect (a) extinction cross-section for multi Fano model (b) E-field efficiency for final model.

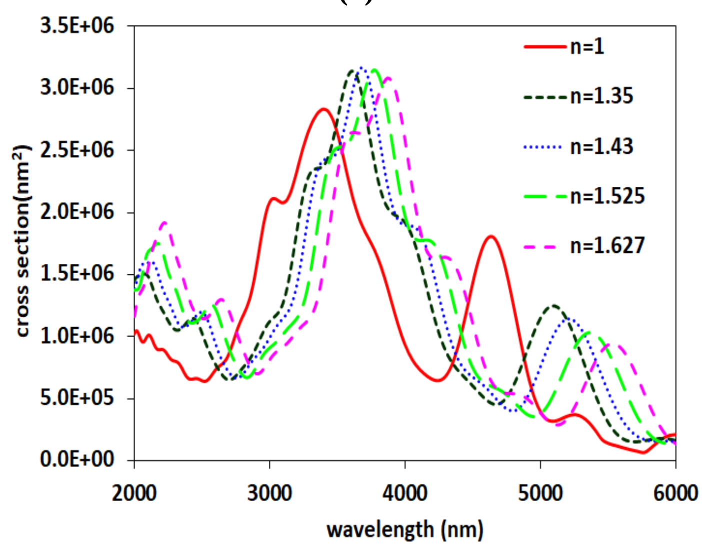
The symmetrical arrangement of the structure can make an independency of the polarization of the incident wave in these nanoparticles. The Final nanoantenna is simulated for two incident wave angles of phi = 0° and 45° and the results are depicted in Fig. 5. The results show similarity at these incident wave angles; however, a frequency shift is visible. In Fig. 5 (a), when the nanoantenna with the incident angle of phi = 45° is excited, the extinction cross-section peak is shifted to the second Fano resonance. Moreover, the nanoantenna has saved its multi Fano generation characteristic. The E-field efficiency is given for phi = 45° in Fig.5 (b), and the second resonance with higher efficiency than phi =0° is visible.



(a)



(b)



(c)

Fig. 6. extinction cross-section for various refractive index (a) ring nan0antenna (b) fractal nanoantenna (c) Final nanoantenna with modified Fano resonance.

The Fano-like dip is attractive for its excellent performance in the near-infrared region (NIR) and also is more distinguishable in bio-materials [28]. FOM is a numerical factor for distinguishing the external material parameter in optical devices for variation of wavelength (Δλ), current density (ΔI), and energy change (ΔE) [29].To obtain the FOM factor, we have coated the antenna with a 60nm biological material. Here, for biological material, we have selected Ether (R–O–R') with n = 1.35, Ethylene glycol ($HO–CH_2CH_2–OH$) with n = 1.43, Chlorobenzene (C_6H_5Cl) with n=1.525, and Quinoline (C_6H_7N) with n = 1.627 [30]. The extinction cross-section for various refractive indexes has been presented for the regular ring nanoantenna, fractal nanoantenna, and final nanoantennas structures in Fig.6 (a), (b), and (c), respectively. It can be seen that the resonances in each of these structures have been shifted to the higher wavelengths. The wavelength shifts in all the resonant modes for all three nanoantennas models for various refractive indexes are compared in Fig.7.

Fig.7 depicts that frequency shift for the final nanoantenna is less than the frequency shift for Fano structure at the dark mode. Typically, the Fano structures are suggested for achieving a higher shift in distinguishing the materials. However, we have proved that when we have used the final model for a solar cell application, we are able to reduce the dust and unexpected material effects on solar cell quality. It is another main benefit of the final nanoantenna in comparison with Fano structures (second model). In addition, Fig.7 shows another aspect of final nanoantenna which is happened in its bright mode. In the final nanoantennas, bright mode shows more distinguishable wavelength shift and it shifts much more than bright and dark modes in the Fano. Therefore, this structure can be developed for dual application such as solar cell and bio-sensing simultaneously. The maximum sensitivity of the final model is 1458 nm/RIU while the maximum sensitivity for the single ring and Fano model are 563 *nm/RIU* and 1058 nm/RIU, respectively.

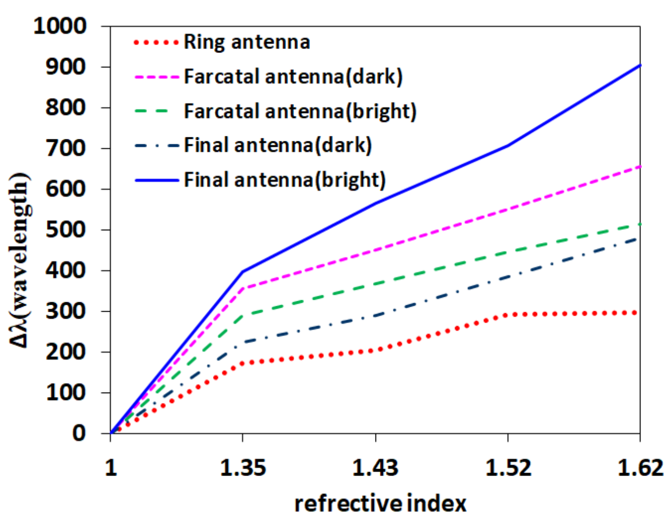


Fig. 7. wavelength shifts for various refractive indexes for all structures in pick resonances.

3. CONCLUTION

In this paper, it was demonstrated how the multi Fano in the nanoantennas can be generated and would be useful for light trapping and energy harvesting. Typically, a few aspects of these techniques were presented. Firstly, the modified nanoantenna (Final antenna) shows great improvement in electric field intensity in comparison with the Plasmonic and multi-Fano response. As the second aspect, the bandwidth of the electric field compared to Plasmonic and a Fano structure was enhanced. So, they may be applied in the solar cell to be active for wider wavelength bandwidth. We have also shown in the Fano structure, the incident wave angle made a shift in resonant frequency and didn't change the field intensity.

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