Intensifying magnetic dark modes in the antisymmetric plasmonic quadrumer composed of Al/Al$_2$O$_3$ nanodisks with the placement of silicon nanospheres

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**Abstract**

In this study, a quadrumer cluster composed of Al nanodisks in both symmetric and antisymmetric orientations has been utilized to generate magnetic hot-spots by using coil-type Fano resonances. Determining the accurate geometrical sizes for the examined cluster, we calculated the spectral response of the structure numerically. Utilizing strong plasmon resonance hybridization between Al/Al$_2$O$_3$ nanodisks that are suited in a close proximity to each other, such a finite and simple nanocluster yields intensified hidden magnetic fields ($|H|$) as a dark mode and electric $|E|$ as a bright modes. Using and placement of silicon nanospheres in the unoccupied gap distance between proximal Al nanodisks give rise to significant enhancement in the energy and quality of the induced multiple Fano dips. Appearing of multiple Fano resonant modes in a coil-type regime in the UV and visible spectrum helps us to optimize the energy of generated magnetic hot-spots, significantly. Ultimately, we examined the sensitivity of the proposed final quadrumer by considering the behavior of Fano minima. We plotted the linear figure of merit (FoM) based on the Fano resonance energy differences in various conditions over the refractive index. Quantifying the FoM for the studied nanostructure, then we compared the quality of structure with the analogous nanoclusters. This work paves novel methods toward the utilization of Al/Al$_2$O$_3$ nanoparticles as a potential substance to employ in designing nanoclusters that are able to support strong dark resonances as well as bright modes. Wide-range working region, optimized electric and magnetic fields, multiple and high quality Fano dips, high FoM and low-costs are the superior features of the proposed artificial structure in comparison to analogous configurations.

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1. Introduction

In the past decade, different fields of optical sciences have witnessed remarkable advances in various branches, and specifically, light-matter interaction in subwavelength dimensions has been considered as one of the major topics in the optical physics that can be described by classical electromagnetic theory [1–3]. Conventionally, the result of an intense interaction between the incident light (at optical frequencies) and the noble metallic structures in the nanoscale dimensions is surface plasmon resonances (SPRs) [1,2]. Newly, well-organized artificial plasmonic molecules or “oligomer” nanoclusters have been proposed as the nanoscale aggregates that can be tailored to support strong plasmon resonances by their subwavelength geometries [4,5]. Considering the specific orientation of these nanoclusters, it is well understood that illuminating closely spaced nanoparticles by a light source with a linear or azimuthal polarizations, a strong hybridization in plasmon resonance modes can be risen due to the interparticle coupling nature, and the result of this interaction is appearing of electric and magnetic dipolar and multipolar modes in the spectral profile of the structure [6–11]. In this regime, a constructive interference between high order collective plasmon resonance modes (actually subradiant dark and superradiant bright modes) gives rise to inducing pronounced Fano resonances in the extinction cross-sectional profile [10,11]. On the other hand, appearing of Fano-like and Fano resonances strongly depends on the structural features of the cluster as well as the quality of interference between subradiant dark and superradiant bright modes. It is strongly verified that robust and high quality Fano resonances can be performed in antisymmetric nanoclusters due to various reasons [6]. Symmetry cancellation in oligomer structures causes formation of new dark modes and an interference of dark magnetic and bright electric resonant modes yields pronounced Fano resonant dips includes an intensification in the energy of the dark modes [12,13]. Earlier works have shown that several antisymmetric oligomer-type structures can be tailored to
support strong plasmon resonances include electric bright resonant modes, however, the magnitude of electric field is superior in comparison to the veiled magnetic field [14,15]. Therefore, researchers mostly considered diverse structures composed of plasmonic nanoparticles or cavities to enhance and optimize the effectiveness of magnetic fields as a dark and hidden mode in plasmonic nanostructures [16].

On the other hand, in searching for new plasmonic substances that can reflect a comparable performance with other conventional and high cost materials (e.g., Au, Ag, Cu), Aluminum (Al) has been suggested, recently. Low-cost, abundance, and CMOS compatible are some of the major attractive features of Al that make it a potential alternative for the mentioned popular materials. It is shown that Al is able to operate in the UV and visible wavelengths efficiently without suffering from dramatic interband transitions and rapid oxidation. In contrast to the Al, Au and Ag show poorer behavior during utilization in the UV spectrum. Newly, Knight et al. [17,18] has investigated the optical response and features of an isolated Al nanodisk in pure and compositional regimes. Besides, it has been comprehensively studied the optical properties of a couple of compositional Al/Al2O3 nanodisks as a simple dimer, and it is proved that Al can be employed in designing artificial plasmonic subwavelength oligomers in compositional regimes include a layer of Al2O3 and SiO2 substrate. Therefore, Al-based nanoparticle clusters are able to support robust plasmon resonance modes around the UV and visible spectra. The ability of supporting coil-type Fano resonant modes by Al clusters to generate enhanced dark magnetic hot-spots has never been investigated until present.

Herein, we utilize an antisymmetric quadrumer cluster composed of Al/Al2O3 nanodisks that are suited in a close proximity (a few nanometers) to each other. Investigating the plasmon response of the proposed Al-based nanocluster, we determine the quality of appeared Fano resonant modes as well as the intensity of bright electric and dark magnetic resonances. Also, we show that the placement of silicon (Si) nanospheres in the unoccupied space between proximal nanodisks of an individual cluster causes red-shifts and enhancements in the performance of induced Fano dips. These controlled modifications and presence of Si nanoparticles give rise to a remarkable increment in the magnetic field intensity, and as a result of this occurrence, a robust intensification in the strength of magnetic hot-spots has been reported. Finite-Difference Time-Domain (FDTD) method (Lumerical FDTD Solutions 8.9) is employed as a numerical model to extract the optical response of the structure. Table 1 contains all of the geometrical parameters in the orientation of nanoparticles and their geometries. To describe and show the shift of plasmon resonant modes by performed structural alterations, we used a dotted linear line through the corresponding profile. For instance, for R = 60 nm, DAl = 10 nm, and 30% of Al2O3 coverage layer, the peak of dipolar electric and quadrupolar magnetic modes are appeared at λ ~ 500 nm and 220 nm, respectively, where the polarization of

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial cell sizes (dx = dy = dz)</td>
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<tr>
<td>Number of time steps (dt)</td>
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<td>Simulation time</td>
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<tr>
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<tr>
<td>Boundary conditions</td>
<td>Perfectly Matched Layers (PML)</td>
</tr>
<tr>
<td>Number of PML layers</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 1

FDTD parameters descriptions and settings.

Table 2

Geometrical sizes and descriptions of a symmetric quadrumer cluster composed of Al nanodisks.

<table>
<thead>
<tr>
<th>Geometrical parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>60 nm</td>
</tr>
<tr>
<td>h</td>
<td>35 nm</td>
</tr>
<tr>
<td>Al2O3 thickness</td>
<td>0.3R</td>
</tr>
<tr>
<td>Host thickness (SiO2)</td>
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<tr>
<td>Gap distance (DAl)</td>
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<tr>
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<td>n = 1.544</td>
</tr>
<tr>
<td>Si refractive index</td>
<td>n = 3.42</td>
</tr>
</tbody>
</table>

2. Results and discussion

Using calculated and ensued data that are presented in Refs. [17,20], we listed all of the essential geometrical parameters in Table 2 for a symmetric quadrumer composed of Al/Al2O3 nanodisks. Therefore, to design an initial quadrumer, we utilized Al nanodisks with an identical radii and height of R = 60 nm and h = 35 nm, respectively, and also, 30% of oxide layer proportional to the radius of an individual nanodisk, which covers the particle entirely. It is well understood that the presence of an oxide layer around the Al nanoparticle gives rise to tremendous localization of surface plasmon resonance energies [17,18]. Due to the unique working region of Al and subcategory components such as oxides etc., the dielectric response of an arbitrary structure based on Al components must be determined and calculated individually. To this end, the dielectric function of a compositional subwavelength structure based on Al/Al2O3 particles has already been determined by using the Bruggeman model. This theory strongly verifies that theoretically measured dielectric function of a compositional structure is in complete agreement with the experimental results [17,19,21,22]. Fig. 1(a) demonstrates a three dimensional picture of the proposed symmetric quadrumer composed of mentioned Al/Al2O3 nanodisks that are deposited on a glass (SiO2) substrate with the thickness of 150 nm and with the refractive index of n = 3.44 and also, all of the nanoparticles are located with an identical gap distance from each other (DAl = 10 nm), which resembles a strong coupling condition. Illuminating the nanocluster with two opposite, linear polarizations (transverse and longitudinal electric polarization modes), we calculated and sketched the scattering cross-sectional profiles for the structure numerically (see Fig. 1 (b) and (c)). Changing the radii of nanodisks homogenously and keeping the ratio of oxide layer as a constant parameter, we examined the effect of these modifications on the appeared and hidden dipolar and multipolar extremes. To this end, we increased the radii of nanoparticles in the range of R = 60 nm to 120 nm, simultaneously. It is clear that increasing the radii of Al nanodisks in the examined quadrumer gives rise to dramatic red-shifts in the position of the quadrupole and dipole extremes to the longer wavelengths. In addition, for nanodisks with the radii of R > 100 nm, a Fano-like dip has been emerged along the scattering diagram and for the biggest radius (R = 120 nm), the pronounced Fano dip becomes deeper and narrower. For such a big radius, a small shoulder has been emerged at the shorter wavelengths, which corresponds to the octupole mode, and a constructive coupling between dipolar and high order modes gives rise to the formation of new dark modes, therefore new Fano dips can be appeared on the scattering spectral profile by controlled and accurate modifications in the orientation of nanoparticles and their geometries. To describe and show the shift of plasmon resonant modes by performed structural alterations, we used a dotted linear line through the corresponding profile. For instance, for R = 60 nm, DAl = 10 nm, and 30% of Al2O3 coverage layer, the peak of dipolar electric and quadrupolar magnetic modes are appeared at λ ~ 500 nm and 220 nm, respectively, where the polarization of
the incident mode is transverse. Then, in the same condition, for a quadrumer composed of nanodisks with the radii of \( R = 120 \text{ nm} \), two distinct extremes regarding the dipolar and multipolar modes at \( \lambda \approx 800 \text{ nm} \) and \( 345 \text{ nm} \) have been reported, respectively. In addition, due to the strength of quadrupole mode energy (dark mode) which results in a constructive interference with the bright mode, a Fano-like resonant mode has been induced at \( \lambda \approx 470 \text{ nm} \). On the other hand, for an incident longitudinal polarization mode, the structure reflects the same response with the prior regime, where the sizes of red-shifts in the position of dipolar and quadrupolar peaks are longer than transverse mode. For instance, in the final regime \( (R=120 \text{ nm}) \), we observed a Fano-like dip at \( \lambda \approx 520 \text{ nm} \), and when we evaluated two Fano-like minima, the quality of Fano minimum during exposing by a linear transverse polarization mode is dominant. The noteworthy point here is that at the bigger sizes of the quadrumer, strong plasmon resonant modes can be supported effectively, but it should be considered that more increments in the size of nanoparticles cause undesired absorption of electromagnetic (EM) field by the structure. This condition also, affects the quality of generated Fano-like dip dramatically, and for \( R=150 \text{ nm} \) \( (R > 120 \text{ nm}) \), the energies of multipolar magnetic modes have been reduced significantly for both of the incidence polarizations, which caused to incomplete hybridization of plasmon modes and a destructive interaction between bright and dark modes at the energy continuum of the bright mode (see Fig. 1(d)). Noticing in the spectral response, a weak octupole peak has been induced for the longitudinal mode, while this peak is absent for the transverse polarization, also, the energy of interference between dark and bright modes have been weakened dramatically that cannot generated Fano dips in both of

![Image](https://example.com/image.png)

**Fig. 1.** a) A three-dimensional snapshot of the symmetric quadrumer composed of Al/Al2O3 nanodisks that are deposited on a SiO2 host, b) numerically calculated cross-sectional profile for the symmetric quadrumer for various nanodisks radii under illuminating by transverse and longitudinal electric polarization modes. The dipolar, quadrupolar, and octupolar extremes are indicated by \( P_d \), \( P_q \), and \( P_o \), respectively, d) scattering cross-sectional diagram for the Al quadrumer while the radii of nanodisks is \( R > 150 \text{ nm} \), under transverse and longitudinal polarization modes, e) two-dimensional snapshots for the plasmon resonance excitation and coupling between adjacent nanoparticles of the quadrumer for both of the bright (i,ii) and dark (iii,iv) modes.
the polarizations. Fig. 1(e) shows numerically obtained two-dimensional snapshots of the electric and magnetic field enhancements correspond to the plasmon resonance excitations (i,ii) and energy coupling (iii,iv) between nanoparticles for the symmetric quadrumer with final geometrical sizes under illuminating with both of the opposite polarizations.

In continue, we studied the same quadrumer composed of Al/Al₂O₃ particles during symmetry breaking. To this end, we utilized three nanodisks with the radii of $R_1 = 120$ nm, while the radius of the fourth nanodisk is variable ($R_4$), also, it should be noted that the height ($h$) of the nanoparticles, gap distance between neighbor nanodisks ($D_{4q}$) and thickness of the oxide layer is constant in all of the future examinations. Due to the subtle difference between transverse and longitudinal polarizations results, we only reported the results for the indecent light with transverse polarization mode due to the high performance of generated Fano resonance dip. A three-dimensional snapshot of the antisymmetric nanocluster is depicted in Fig. 2(a), which includes all of the geometrical parameters. Fig. 2(b) demonstrates the scattering cross-sectional diagram for the antisymmetric quadrumer, while the radius of the fourth nanoparticle ($R_4$) is increasing in the range of 220–400 nm. For instance, for $R_4 = 220$ nm and 280 nm, despite of symmetry breaking in the structural properties of the quadrumer, the energy of magnetic dark mode is still low and we only observed a weak Fano-like dip along the scattering diagram at $\lambda \sim 525$ nm and 575 nm, respectively, where the peak of octupole has been appeared with an insignificant energy. The interesting event here is that the octupole magnetic dark mode with the higher energy can be coupled efficiently to the electric bright mode, and the resultant of this constructive interaction is formation of second Fano-resonant mode in the spectral profile. This occurrence can be performed efficiently by introducing additional structural modifications that will be discussed further. Considering depicted two-dimensional snapshots that are illustrated in Fig. 2(c), the quality of energy coupling and plasmon resonance excitation are depicted for both of the electric and magnetic modes. In these figures, also, we realized the intensity and quality of energy coupling between proximal Al/Al₂O₃ nanodisks in the antisymmetric nanocluster. Next, increasing the size of $R_4$ to 340 nm, due to the owning of adequate plasmon resonance energy by quadrupole mode, hence, a deep and pronounced Fano resonant mode can be formed along the scattering efficiency diagram. In this regime, an octupole dark mode has been observed with a significant energy in comparison to the earlier investigations, however, it still cannot be coupled to the bright mode constructively and effectively, and as a result, a second Fano minimum
has not been reported. The other important phenomenon here is the red-shift in the position of dark and bright modes as well as the Fano and Fano-like dips to the longer wavelengths by increasing the size of the fourth nanodisk. The last modification is for the big nanodisk with the radius of $R_b = 400$ nm, and noticing in the spectral response of this adjustment (see Fig. 2(b)), the energies of dipolar and multipolar modes have been reduced dramatically, and this undesired result can be ascribed to the destructive internal damping of the EM field (absorption) by the bigger nanodisk. Consequently, the Fano dip becomes broader and shallower, hence, due to the tremendous reduction in the energy of Fano resonant mode, it cannot be considered as a Fano-like dip anymore (indicated by a question remark). In this regime, due to the high ratio of the absorption of the incident light energy, the octupole extreme is going to become negligible. Fig. 2(c), also, demonstrates the quality of energy coupling for both of the electric and magnetic modes, and for the latest study, and the intensity of magnetic field $|H|$ has been increased and decreased by changing the size of fourth nanoparticle of the quadrumer. Evaluating the proposed nanocluster performance with analogous nanostructures such as antisymmetric trimers with Au and Ag nanoparticles, the superior behavior of the suggested nanostructure is manifest and

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**Fig. 2.** a) A three-dimensional snapshot of the antisymmetric quadrumer composed of Al/Al$_2$O$_3$ nanodisks that are deposited on a SiO$_2$ host, b) numerically calculated cross-sectional profile for the antisymmetric quadrumer for the bigger nanodisk with a variable radius under illuminating by a transverse polarization modes, c) two-dimensional snapshots for the plasmon resonance excitation and coupling between adjacent nanoparticles of the antisymmetric quadrumer for all of the examined radiuses, d) scattering cross-sectional diagram for modifications in the size of gap distance.
also, has a strong potential to be enhanced by additional structural modifications. In continue, we examined the possibility of formation of deeper and narrower Fano resonant modes and even multiple Fano dips by the same antisymmetric quadrumer.

The other important parameter in the presented antisymmetric quadrumer is the size of gap distance between proximal Si nanoparticles. In all of the presented investigations, the size of the gap distance is set to an identical value between all of the nanoparticles. It is well understood that reducing the size of gap distance yields strong localization of plasmonic magnetic and electric resonant modes in the unoccupied space between neighbor nanoparticles [23,24]. To examine the effect of this parameter on the quality of appeared plasmon modes and Fano resonances, we plotted the scattering cross-sectional profiles for the antisymmetric quadrumer during modifications in the size of gap distance. Fig. 2(d) exhibits numerically calculated cross-sectional profile for the structure from weak coupling (big gap distance) to strong coupling (small gap distance) regimes. Obviously, decreasing the size of gap distance causes strong coupling between excited electric and magnetic modes, and this condition is resulted with deep Fano dips. Noticing in this diagram, for bigger sizes, the energy of multipolar peaks are weak dramatically, and even absent ($P_n$ for $D_{eq} = 40 \text{nm}$). For the gap distances smaller than $10 \text{nm}$ ($D_{eq} < 10 \text{nm}$), the quality of Fano dip has been decreased due to losing of unoccupied space between proximal nanoparticles for the interference of magnetic and electric plasmon resonant modes. In this regime, more decrements in the size of gap distance give rise to blue-shift of dipolar and multipolar extremes to the shorter spectra includes a dramatic decrement the intensity of Fano resonance and multipolar extremes. Therefore, finding an appropriate size for the gap distance helps to keep the strength of resonance in a robust regime, while the energy of Fano dip intensified ($D_{eq} = 10 \text{nm}$).

It is verified that the placement of dielectric and semiconductor nanoparticles to a given nanocluster can enhance the performance of the structure significantly. Recently, Wen et al. [25] verified that addition of Carbon (C) dielectric nanospheres between the unoccupied (gap distance) space between closely spaced decamer nanocluster composed of Gold (Au) nanodisks gives rise to tremendous accuracy in refractive index sensing applications by inducing high quality and narrow Fano dips. Herein, we try to employ crystalline Si nanospheres with the refractive index of $n = 3.42$ in designing an optimized quadrumer nanocluster that can be tailored to support strong plasmon resonances to generate intensified magnetic hot-spots using appeared coil-type Fano resonant modes. To this end, we utilized previously examined the optimal antisymmetric structure with the following geometrical dimensions: $R_p = 340 \text{ nm}$, $R = 120 \text{ nm}$, $h = 35 \text{ nm}$, and $D_{eq} = 10 \text{ nm}$, and also, we used Si nanospheres with the radii of $R_s = 5 \text{ nm}$ that are suited between smaller and the biggest Al nanodisks in touching regimes, however, these Si particles provide a bridge between two proximal nanodisk, as illustrated in a three-dimensional schematic (see Fig. 3(a)). In this case, due to the significant increments in the dielectric function, we observed a remarkable intensification in the strength of near-field coupling between adjacent nanoparticles. Placement of Si nanospheres yields additional derangement and asymmetricity in the proposed inherently antisymmetric quadrumer, hence, we expected the appearance of new dark modes and consequently, sharp and high quality Fano minima. In this case, first, we consider the effect of Si nanospheres placement in the presence of a sole nanosphere only, while the other spheres are absent. Employing this method, we are able to

![Fig. 3.](image)

- **Fig. 3.** a) A three-dimensional snapshot of the antisymmetric quadrumer composed of Al/Al2O3 nanodisks that are deposited on a SiO2 host with the placement of Si nanospheres in the gap distance space between quadrumer Al nanoparticles, b) numerically calculated cross-sectional profile for the antisymmetric quadrumer for the presence of a sole and three Si nanospheres under illuminating by a transverse polarization modes, c) the magnetic field $|H|$ efficiency diagram for the final antisymmetric quadrumer with Si nanoparticles, and the field is intensified in the Fano zones. Inset is the two-dimensional picture which illustrates the charge current $|J|$ direction through the nanoparticle in the Fano zones, d) two-dimensional snapshots for the plasmon resonance excitation and coupling between adjacent nanoparticles of the quadrumer with the presence of Si nanoparticles for both of the electric and magnetic modes under transverse electric mode excitation.
follow the reflection of the cluster to the presence of Si nanosphere during illuminating by a transverse polarization mode. Fig. 3(b) illustrates calculated scattering cross-sectional profile for the cluster in the presence of a Si nanoparticle. Noticing in the corresponding diagram, two strong extremes correspond to the dipole and quadrupole modes have been reported, also, due to the constructive interference between dark and bright resonant modes, a narrow Fano dip is generated at $\lambda \approx 555$ nm. We, also, perceive a shoulder that is appeared as a distinct mode at the shorter wavelengths: an octupole modes’ peak ($\lambda \sim 280$ nm). This multipole extreme causes formation of a Fano-like dip at $\lambda \sim 340$ nm due to the constructive interference of its energy with the electric bright mode. These multiple Fano resonant modes open new gates to introduce enhanced magnetic hot-spots at the gap distance space between nanoparticles units. Then, we determined the effect of the presence of three Si nanospheres simultaneously at the specified locations by drawing the scattering spectra in the Fig. 3(b). This figure also includes a schematic picture of the antisymmetric quadrumer with the placement of a sole and three Si nanospheres, separately. The outstanding occurrence here is the inducing of two strong Fano resonant modes along the spectral response of the structure at $\lambda \sim 420$ nm and $\lambda \sim 665$ nm. It is well understood that appearing of a sole Fano minimum gives rise to generation of optimized magnetic hot-spots. Herein, by introducing of new Si nanoparticles, we generated two strong Fano dips that are able to yield highly optimized and enhanced magnetic hot-spots at the UV to the visible spectrum. To provide a comprehensive study, we calculated and depicted the magnetic field $|H|$ efficiency over the wavelength variations. The substantial subject here is the position of Fano dips that the magnetic field has been intensified in these zones. Comparing Fig. 3(b) and (c), it is understandable that between the onset points of the multiple Fano dips and their termination points, a dramatic enhancement in the magnetic field energy has been performed. The inset picture illustrates the conduction current density direction $J_{c}$ through the antisymmetric quadrumer, and as we expected, at the Fano zones, the direction of conducted current is completely opposite in each one of the particles of the cluster. This schematic illustrates the method of charge distribution and formation of the multiple coilt-type Fano resonances through the subwavelength quadrumer cluster in a circulating regime. The role of Si nanoparticles here is the intensifying coupling intensity between proximal nanoparticles and due to the size of these particles they cannot change the current density distribution direction significantly. Fig. 3 (d) shows a two-dimensional snapshot of plasmon resonance coupling and significant intensification in the collective magnetic plasmon modes by the structure in the recent orientation. Noticing in these simulation snapshots, the strength and quality of the plasmon resonance excitation and coupling intensity between the proximal Al/Al$_2$O$_3$, nanodisks have been improved by addition of Si nanoparticles to the antisymmetric quadrumer. Analyzing the performance of the proposed quadrumer and comparing its features with analogous clusters, the superior behavior of the proposed nanostructure is manifest. Low-cost, CMOS compatible, and easy fabrication are the most important advantageous of the Al-based nanocluster.

Nanoparticle clusters in various orientations have been extensively employed in designing ultra-sensitive plasmon resonance sensors in nanoscale dimensions [26,27]. It is well accepted that plasmonic structures based on noble metallic nanoparticles such as Au and Ag provide sharp Fano dips with high value for figure of merit (FoM) [26–28]. Ahmadivand et al. [28] newly provided a method to utilize compositional arrangements of Al/Al$_2$O$_3$ nanoparticles in a cluster orientation to hybridize the plasmon resonance energy in self-assembled clusters. Herein, we measure the sensitivity of LSPR sensing based on generated magnetic hot-spots. To this end, we altered the refractive index of the ambient to measure the Fano resonance energy in its maximum and minimum energy values ($\Delta E$ (eV)). We showed that increasing and decreasing the refractive index of the environmental substance give rise to red and blue-shift of Fano resonances to the longer and shorter spectra. Fig. 4 illustrates the scattering cross-sectional profile for the quadrumer structure with the inserted Si nanoparticles during immersing by various liquids as following: CH$_3$COCH$_3$ (Acetone) $n=1.351$, C$_4$H$_8$O (Butanol) $n=1.399$, and C$_6$H$_5$ (Benzene) $n=1.501$. Obviously, by increasing the refractive index of the surrounding medium Fano minima red-shifted to the longer wavelengths, while the Fano dips become sharper and deeper. Inset diagram shows the calculated FoM for the quadrumer cluster in antisymmetric orientation, which sketches the measured energy difference between appeared Fano modes over the refractive index variations. Numerical calculation results verified that the FoM here is approximately $\sim 6.65$, which is higher than other analogous quadrumer type structures. It should be noted that this value is obtained for a structure based on Aluminum and Si components without using regular and costly plasmonic materials such as Ag and Au. Comparing the obtained FoM with the other similar types of symmetric quadrumers composed of nanoparticles and nanocavities [26,29], we verified that the proposed structure provides superior ultra-sensitivity in the same conditions. This understanding paves a method to employ a well-organized and simple antisymmetric quadrumer clusters composed of Aluminum nanodisks with the placement of Si nanospheres to provide intense magnetic hot-spots for sensing applications with a significant accuracy.

3. Conclusions

In this article, we examined the optical properties of a quadrumer nanocluster composed of Al/Al$_2$O$_3$ nanodisks in symmetric and antisymmetric regimes. We verified that using accurate geometrical sizes for a well-organized symmetric structure helps us to introduce dark and bright modes in the scattering efficiency profile of the proposed structure. Breaking the symmetry of the quadrumer and illuminating the cluster, we observed the appearance of new magnetic dark modes, and the resultant of constructive coupling between dark and bright modes is the formation of Fano-like and Fano dips as coil-type resonant modes in the spectral response of the structure in the UV spectrum. We
demonstrated that with the placement of Si nanospheres in the gap distances between Al nanoparticles, a significant enhancement in the quality of the Fano dips can be performed due to the increments in the dielectric function. In the case of adding Si nanoparticles to the plasmonic quadrumer, new multipolar dark modes (octupole modes) have been reported as well as dipolar and quadrupolar modes, which originates from the constructive and robust near-field coupling between Al nanodisks. All of these intensifications in the energy of coil-type Fano resonances directly give rise to a significant enhancement in the energy of hidden magnetic dark modes. This structure has a strong potential to employ in various applications from refractive index sensing to the nonlinear spectroscopy and superlensing purposes.

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References


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