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An elliptical dipole nanoantenna with an elliptical slot for enhanced plasmonic performance

***Abstract**. The increasing interests in plasmonic nanoantennas focus on changing the resonance wavelength or field localization by changing the shape and size of the nanoantenna. A hollow elliptical dipole nanoantenna (HEDNA) is proposed by adding a slot in the two elliptical arms of the dipole nanoantenna. The plasmonic resonance wavelength and the localized field in the gap zone are increased. Moreover, the slot can be designed to enhance the overall absorption and reduce scattering. The simulations revealed that the antenna with the slot HEDNA scatters just 43% of the incident power and absorbs the remaining 57%, while the parent solid dipole scatters 90% of coupled power and absorbs the residual 10%. This represents switching from a scatterer to an absorber nanoantenna. Moreover, the achieved field enhancement in the gap region of the HEDA is more than three folds that without a slot. The proposed structure is easily applicable in sensing, thermoplasmonics, solar cells, and energy harvesting.*

***Streszczenie.** Rosnące zainteresowanie nanoantenami plazmonicznymi koncentruje się na zmianie długości fali rezonansu lub lokalizacji pola poprzez zmianę kształtu i rozmiaru nanoanteny. Zaproponowano wydrążoną eliptyczną nanoantenę dipolową (HEDNA) poprzez dodanie szczeliny w dwóch eliptycznych ramionach nanoanteny dipolowej. Zwiększa się długość fali rezonansu plazmonowego i zlokalizowane pole w strefie szczeliny. Ponadto szczelinę można zaprojektować tak, aby zwiększyć ogólną absorpcję i zmniejszyć rozpraszanie. Symulacje wykazały, że antena ze szczeliną HEDNA rozprasza zaledwie 43% padającej mocy i pochłania pozostałe 57%, podczas gdy macierzysty stały dipol rozprasza 90% sprzężonej mocy i pochłania pozostałe 10%. Oznacza to przejście z nanoanteny rozpraszającej na nanoantenę pochłaniającą. Co więcej, osiągnięte wzmocnienie pola w obszarze szczeliny HEDA jest ponad trzykrotnie większe niż bez szczeliny. Proponowana struktura jest łatwa do zastosowania w wykrywaniu, termoplazmonice, ogniwach słonecznych i pozyskiwaniu energii. (**Eliptyczna nanoantena dipolowa z eliptycznym gniazdem dla zwiększenia wydajności plazmonicznej**)*

Keywords: nanoantennas, Scattering, Absorption, plasmonic, resonance wavelength, energy harvesting.
Słowa kluczowe: antena eliptyczna, nanoantena

Introduction

Through the miniaturization of antennas, nanotechnology has enabled the subwavelength engineering of light devices. The capacity of plasmonic nanoantennas to react to incident light through the concept of localized surface plasmon resonance LSPRs was discussed by many workers [1][2][3][4][5][6]. Researchers have efficiently used the coupling between adjacent parts of the metallic nanoantenna, or the coupling between nanoantenna elements employed in array designs for further field enhancement of the nanoantennas [7][8][9][10]. The aims were to enhance properties like the Full-Width at Half-Maximum (FWHM), sensitivity, absorption, and scattering ratios, as well as field localization.

The nanoantennas were also utilized to increase the effectiveness of infrared (IR) sensors due to their high absorption rate [11][12], surface-enhanced IR absorption [13], and IR energy harvesting capability [2][14][15]. To achieve better performance, triangular[16][17][8], square [18], rectangle [19], elliptical, and circular [18] shapes were examined. Most of these works investigated nanoantennas having solid shapes [20], while [19] took into consideration both solid and hollow rectangles in the form of rings. The aims of the investigators were to attain better performance as larger bandwidth, better localization of the field, and better absorption and lower scattering characteristics.

This work aims to investigate the effect of adding a hole to the arms of the conventional elliptical disc dipole nanoantenna. The introduction of the hole increases the design freedom and can be used to control the absorption and scattering of the nanoantenna. Investigations were carried out into how the hollow area parameter can affect the resonance wavelength, scattering, absorption, FWHM, and the electric field in the gap region. The study shows that the proposed design can be utilized to modify the scattering and absorption properties without enlarging the antenna size. The achievements are boosting absorption and reducing scattering. The CST Microwave Studio Suite 2016, which applies the finite integration technique, was used in the modeling and optimization of the characteristics of the proposed hollow elliptical dipole nanoantenna HEDNA.

The hollow elliptical dipole nanoantenna

The proposed hollow elliptical dipole nanoantenna (HEDNA) geometry is shown in Figure 1, where the dipole has two elliptical arms with holes to form elliptical rings. By altering the width of the ring or the size of the hole, a new design parameter or an extra degree of freedom is obtained. This added parameter can be used to tune the response while keeping the other parameters of the nanoantenna unchanged. The dimensions of the elliptical dipole nanostructures are shown in Figure 1, where h is the height, and t is the width of the silver ring. The two rings are separated by g, and R1 and R2 are their outer major and minor axes respectively.

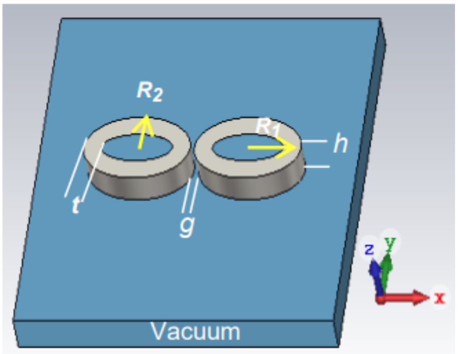

Fig.1 The geometry of the proposed HEDNA in free space.

The Drude model, which heavily emphasizes the free electron that metals possess and which generates surface plasmon resonance, was used to represent the properties of silver materials. It has been established that materials with more free electrons than bound electrons are better suited for the Drude free electron model. Then, the silver nanoantennas height *h* is set to 25nm to provide a strong plasmonic effect, where the metal thickness must be comparable to the metal skin effect [21]. The nanoantenna was stimulated by wave excitation utilizing x-polarized light traveling in the inverse z-direction (wave incident from the top of the HEDNA. The effect of the hollow region on the resonance wavelength, absorption, scattering, FWHM, and the confined electric field in the gap region was examined by creating an elliptical hollow region in an EDNA with a fixed minor radius of 30nm and a major radius of 50nm. The outer dimensions *R1* and *R2*, gap g, and thickness h were held constant in the simulations, at (*R1*=50nm, *R2*=30nm, *g*=4nm, and *h*=25nm), while the hollow region was adjusted in steps (between solid case to a slim ring having width *t*=3nm). The filled EDNA (solid case) is represented by the case without holes. The obtained results of the simulations are presented in the following sections.

Scattering and absorption in the nanoantenna

The first set of the simulation results is shown in Fig. 2, where the width *t* of the ring was changed from *t*=3nm (thin ring) to filled ring (solid disc). The displayed results are the absorption cross-section *ACS* and the scattering cross-section *RCS*. It can be seen from the figure that the absorption cross-section *ACS* increases, as the ring width is reduced, while at the same time, the scattering cross-section *RCS* decreases. Thus, the main feature of the ring behavior changes from scattering towards absorption as the disc is transformed into the shape of a ring and towards a thinner ring. When the inner hole region extended where the width of HEDNA becomes less than 5nm, the *ACS* eventually surpassed the scattering cross-section RCS as shown in Fig.2 e. It is clear from Fig.2 that the parent solid EDNA scatters 90% of coupled power and absorbs the remaining 10%. In contrast to the hollow structure HEDNA, scatters just 43% of the linked power and absorbs the remaining 57% at width *t*=5 nm. The resulting hollow elliptical nanoantenna geometry, with various widths *t*, can enhance the overall dipole nanoantenna's absorption and reduces its scattering.

By contrasting the two cross-section metrics with the well-known case of a metal sphere of diameter a, the nanoantenna can be connected to the antenna parameters as [22]:

(1) $$ACS = K\,Im[\alpha] = 4\pi K\, a^3 Im\left(\frac{\varepsilon_m - \varepsilon}{\varepsilon_m + 2\varepsilon}\right)$$

(2) $$RCS = \frac{K^4}{6\pi}|\alpha^2| = \frac{8\pi}{3}K^4 a^6\left|\frac{\varepsilon_m - \varepsilon}{\varepsilon_m + 2\varepsilon}\right|^2$$

Where ε_m and ε are the permittivities of the metal sphere and the surrounding medium, respectively. $K=2\pi/\lambda$ and a is the diameter of the sphere, and α is the polarizability [23].
The extinction cross-section is the sum of the scattering cross-section and absorption cross-section [23]:

(3) $$Ext = ACS + RCS$$

Figure 3 shows the relative values of both the absorption cross-section ACS and scattering cross-section RCS of the proposed hollow elliptical dipole nanoantenna HEDNA. The figure displays the ratio *RCS/ACS*. It can be seen that the scattering cross-section exceeds the absorption cross-section (ratio larger than 1) for the elliptical dipole widths that are larger than 5 nm. Larger inner holes or thinner nanoantennas result in more absorption and less scattering. The blue-tinted zone reflects the best region for the incident light uptake for localized surface plasmon resonance LSPR enhancement, where *RCS/ACS* ratio values range from one to three [24][25][19]. This relationship will be explained later when the process of localized field enhancement is addressed. Therefore, a hollow region can be included in a suitable EDNA size to create an HEDNA in which the absorption and scattering cross-sections can be tailored by the designer to the desired values at the operating frequency.

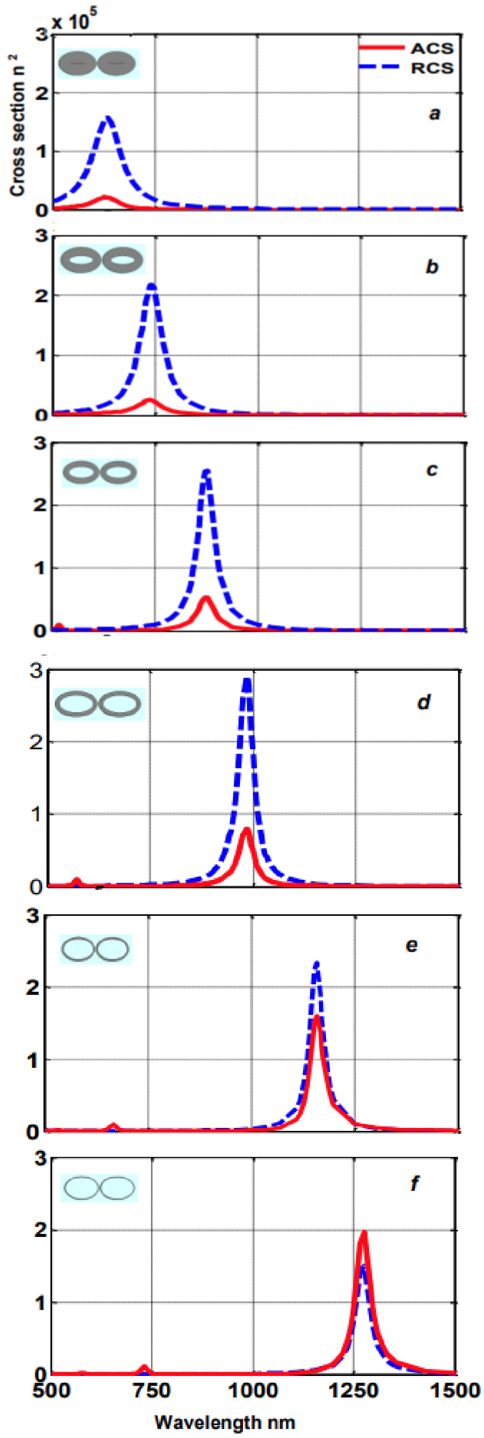

Fig. 2: Effect of the hollow elliptical region on the absorption crosssection (ACS) and scattering cross-section (RCS): (a) t=s (solid dipole), (b) t=20 nm, (c) t=15 nm, (d) t=10 nm, (e) t= 5nm, and (f) t= 3nm. At R1=50nm, R2=30nm

HEDNA resonance wavelength

Resonances with large responses are visible in the dipoles' response to the incident light. Figure 4 shows the relationship between resonance wavelength and the ring width *t* with constant outer dimensions (*R1*=50nm, *R2*=30nm, and *h*=25nm). It is evident that the resonance wavelength has been increased (red-shifted) as the hole size increases (thinner elliptical nanoantenna). In these dimensions, the HEDNAs resonant wavelength varied from 620nm to 1300nm, where the average circumference of the ring was changed from 250 nm to 180 nm. The shift of the resonance wavelength with increasing the hole size was noticed in [26], where the holes were made in the form of triangles as part of the Sierpinski fractal geometry. With the ring shape, the resonance wavelength is linked to the average circumference of the ring rather than the diameter of the ring or the solid disc.

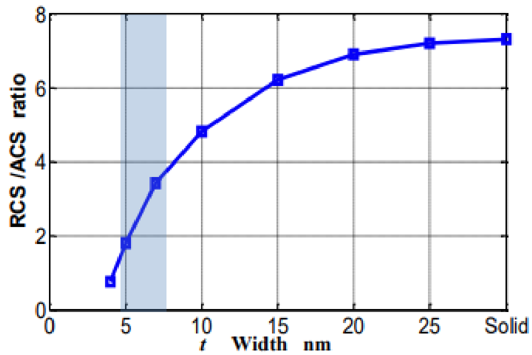

Fig. 3 Variation of the RCS /ACS ratio with the width t of the ring at R1=50nm, R2=30nm.

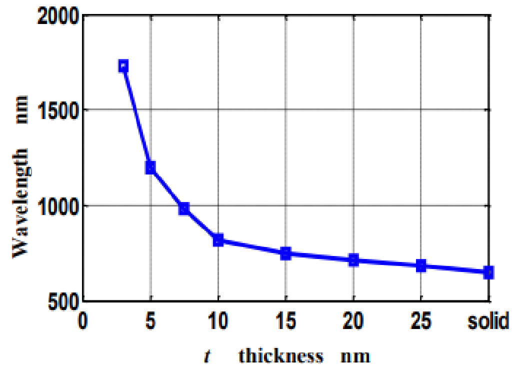

Fig.4 Variation of the resonance wavelength with the size of the elliptical hollow region (width of the ring t).

Assessment of the FWHM

The sharpness of the resonance curves that are displayed in Fig. 2 can be evaluated by measuring the full width at half maximum FWHM. This is expressed by the difference between the two wavelengths at which the response is at half of its highest value:

(4) $$FWHM = \lambda_2 - \lambda_1$$

Where λ_1 and λ_2 are the wavelengths at which the response is at half its highest value. This expresses how narrow is the response of the nanoantenna. As shown in Fig.5 the FWHM decreases as the hollow region is increased (the ring becomes thinner) and the FWHM ranged from 100nm to 32 nm for the solid EDNA and the ring with *t*=4 nm respectively. As a result, one may assess various designs while also taking into account the FWHM values. Our new approach to the proposed structure had a decent FWHM when compared to findings of [26] [27] [28] and [29] as shown in Table 1.

The other important parameter of the resonance response is the quality factor Q defined as:

(5) $$Q = \lambda o/FWHM$$

Figure 5 shows the variation of the quality factor Q with the width of the ring t. The quality factor increases as the size of the hollow region is increased.

Our new approach to the proposed structure has a decent FWHM when compared to the finding in published results of various dimensions as shown in Table 1. This demonstrates that our findings are highly promising compared to the published results.

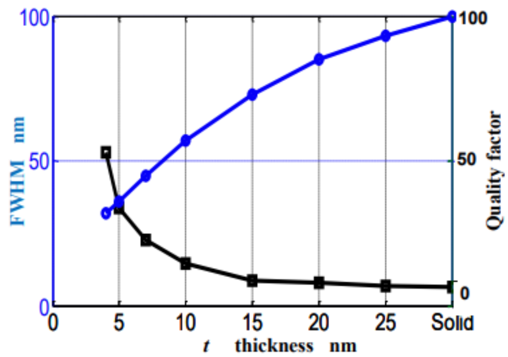

Fig.5 Effect of the elliptical hollow region on the FWHM (blue curve) and quality factor (black curve) for various widths *t*.

Table 1 Comparison of the FWHM of the proposed HEDNA with those of published works.

Ref.	Designed nanoantenna	FWHM
[8]	Triangular Bowtie	54-80
[27]	Square Shape	125
[26]	Triangular Bow-Tie Sierpinski fractal slots	280
[28]	Disk Shape	109-118
[29]	Elliptical Antenna	95-100
proposed	HEDNA	32-100

Field Intensity in the gap region

There are many applications for the plasmonic devices where the localization of the electric field is of main concern. The distribution of the electric field intensity at the gap region of the HEDNA for various hollow region sizes or different ring widths *t* is shown in Fig.6. The obtained results of three designs of the HEDNA (Figs. 6, b,c,d) are compared to that of the solid elliptical dipole (Fig.6a). It can be easily seen that the field intensity in the gap region is larger than those at other regions, thus proving a good localization of the electric field. The figure shows clearly the effect of the hollow region on the field density, where different values of the maximum electric field are achieved for the various widths t of the ring.

Figure 7 demonstrates how the size of the hole affects the incident light coupling to the HEDNA. Peak surface plasmon resonance occurs at specific widths of the HEDNA *t* values where the absorption is two to three times larger than the scattering, providing the highest overall field intensity (peak value) in the gap zone (according to the blue shadowed region in Fig.3). The maximum field intensity (at *t*=7nm) is over 3 times that of the solid EDNA. As the hole size increases, the field intensity in the gap region tends to rise, demonstrating that the absorption outperforms scattering. The HEDNA benefits from this ability to concentrate the electric field in the gap region.

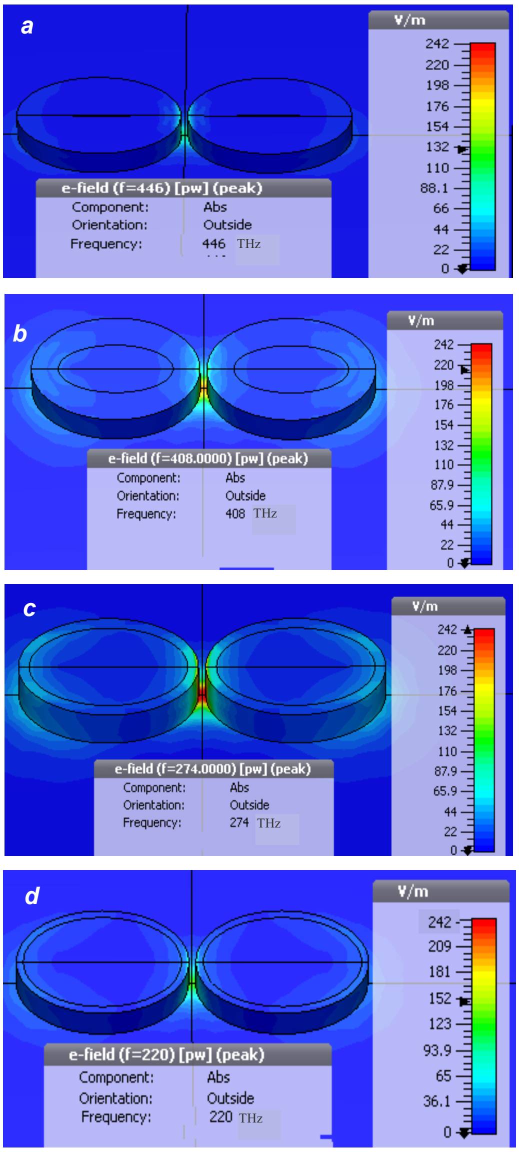

Fig. 6 Variation of the field intensity at the resonance wavelength for various inner hollow region sizes:
(a) *t*=s (solid), (b) *t*=15 nm, (c) *t*=7 nm, (d) *t*=4 nm.

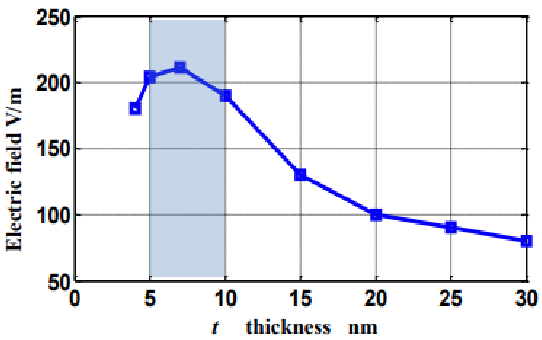

Fig.7 Variation of the maximum value of the electric field intensity in the gap region with the size of the hollow region (width of the ring t).

Conclusions

This research has shown that the scattering and absorption properties of a nanoantenna can be altered by adding an elliptical hole inside the parent elliptical dipole nanoantenna EDNA. The major objective is to determine the scattering and absorption ratio that produces the highest field concentration in the hollow elliptical nanoantenna HEDNA gap region due to LSPR.

In the parent EDNA, scatter accounts for 90% of the coupled power by the nanoantenna, and the remaining 10% is absorbed by the nanoantenna. The scattered coupled power in the proposed hollowed EDNA, however, reaches 43% and the remaining 57% is then absorbed. Applications for sensing and spectroscopy benefit greatly from the simultaneous prevention of scattering and augmentation of absorption that occur in HEDNA. When the coupling to the incident light is at its highest while the scattering cross-section is at its lowest value, the elliptical nanoantenna's gap achieves the best enhancement in the plasmonic localized field, which is consistent with the results of earlier studies.

Another characteristic is that the resonance wavelength can be altered by varying the size of the hollow region. In fact, that HEDNA's resonance wavelength is larger than it was before placing the hole (solid elliptical nanoantenna) where it is extended from 620nm to 1300nm with inherently FWHM that ranged from 100nm to 32nm. Additionally, the hollowed design can be implemented in several nanoantenna geometries using easily accessible characteristics and used in a variety of applications.

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