Phys. Scr. 95 (2020) 055507 (8pp) https://doi.org/10.1088/1402-4896/ab7850

High-order magnetic modes and multiple Fano resonances generation by a Fish-like dimer nanostructure

Xueying Jiang, Yiping Huo, Chen Zhou, Yiyuan Guo, Yibo Hou and Qiqiang Niu

School of Physics and Information Technology, Shaanxi Normal University, Xi'an 710062, People's Republic of China

E-mail: yphuo@snnu.edu.cn

Received 9 December 2019, revised 16 February 2020
Accepted for publication 20 February 2020
Published 3 March 2020

Abstract

Various noble metal nanostructures based on surface plasmon have been proposed in recent years. Under the irradiation of incident light, if the oscillation frequency of the electrons on the metal surface matches the frequency of the incident light wave, resonance will occur. In the resonance state, a special electromagnetic mode is formed: the electromagnetic field is localized and enhanced in a small area of the structure surface. In our artic, a fish-like dimer (F-LD) nanostructure has been proposed. The dark second order magnetic mode is excited due to the near-field coupling between two parts of the dimer. An asymmetry Fano linetype will be generated when the dark magnetic mode is coupled with the bright electric mode. Rotating the structure, the fourth and sixth order magnetic modes can be generated. When the radii of the semi-rings in the gap are changed, the first and third order magnetic modes can be observed. More interestingly, as the number of semi-ring in the gap increasing, the spectral line shape can be controlled and higher-order magnetic modes can be generated regularly. At the same time, multiple Fano resonances can be observed in the extinction spectrum and the spectrum can be modulated simultaneously in multiple bands. By changing the structure parameters, the first, second, third, fourth, sixth and eighth order magnetic modes can be obtained. In different cases, the magnetic field can be enhanced greatly in different areas of the gap, and the maximum magnetic field enhancement reaches 49 times of the incident field. For these characteristics, our structure can be well used in multi-band sensing and surface enhanced spectroscopy.

Keywords: high-order magnetic modes, multiple fano resonances, plasmonics

(Some figures may appear in colour only in the online journal)

1. Introduction

Plasmonics is an interdisciplinary subject combining surface plasmon and photonics, which is called the most potential information carrier of nano-integrated photon devices. Compared with the traditional optics, plasmonics is studied at the nanoscale, which can manipulate light at the nanoscale without the limitation of diffraction limit. Plasmonics has a very important application prospect in many research fields, such as surface enhanced fluorescence, surface plasmon photon chips, couplers, biosensor, optical filtering and so on.

Surface plasmon is an electromagnetic wave, which is generated by collective oscillations of photons or electrons [1, 2]. As a bridge between photons and electrons, it provides an opportunity to construct subwavelength integrated photonic devices for quantum communication and processing [3–6]. When metal nanostructures are close to each other, their respective plasmons will interact to form a hybridized collective mode. The interferences between different plasmon modes of coupled nanostructures can bring about some interesting phenomena, such as Kerker effect [7], Hanle effect [8], plasmonic Fano resonance [9–11], high-order

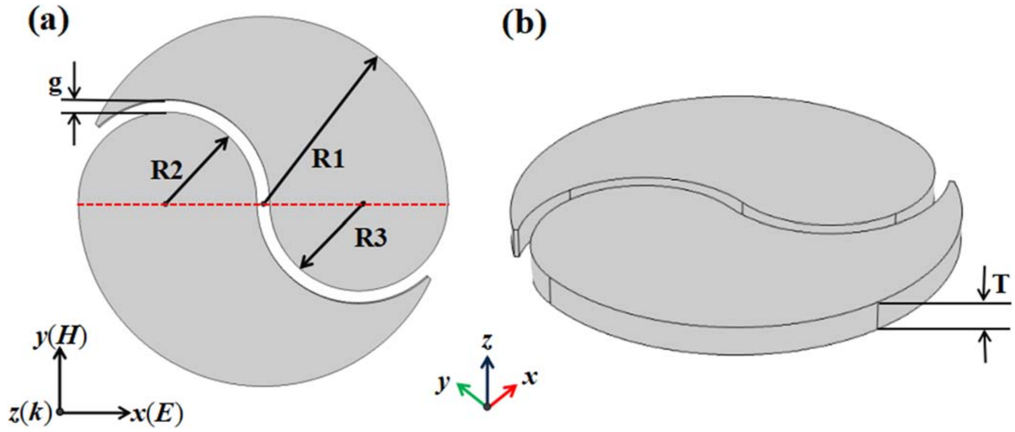

Figure 1. (a) 2D graph of the F-LD nanostructure and the geometrical parameters. (b) 3D graph of the F-LD.

electromagnetic mode [12], and second harmonic generation etc [13].

Fano resonance, as a fundamental resonance effect, has been extensively studied in various nanostructures, such as ring-disk [14, 15], nonspherical assemblies [16], ring-rod nanostructures [17], plasmonic oligomer clusters etc [18]. In the plasmonic system, Fano resonance arises from the coherent interference between the broadband bright mode and the narrowband dark mode [18, 19]. The bright mode can be directly excited by incident light, and it has a large net dipole moment. However, the dark mode can not be excited directly, which can only be excited by near-field coupling or symmetry breaking. The net dipole moment of dark mode is almost zero. Usually, a series of excellent properties will be induced when the plasmonic Fano resonance is generated such as large local field enhancement, high sensitivity to surrounding environment or structural parameters, large absorption or transmission of light at resonance frequency, etc. Benefiting from these characteristics, Fano resonance has been widely used in various fields including surface enhanced spectroscopy [20, 21], Fano switch [22], Fano interferometer [23], ultrasensitive biosensor [24, 25] and so on. A crisscross dimer nanostructure has been proposed by Zhang *et al*, in which a tunable Fano resonance can be generated. More interestingly, large electric field enhancement can be excited at the same position at each plasmon resonance, which have important application value in the field of surface-enhanced spectroscopy [18]. Another silver nanoring structure has been proposed by Yi *et al.* The absorption intensity and the resonance peaks can be changed by adjusting the radius (inner radius and outer radius) and height of the structure. In addition, the dipole, fourth-order and eighth-order plasmon resonance modes can be observed in spectrum, which is an important step toward a thorough understanding of plasmon resonance [26].

Up to now, most of the research on high-order plasmonic resonance is about electric modes. However, high-order magnetic modes are also important in plasmonic materials and devices [27]. It has been testified that optical frequency magnetic plasmonic resonance can improve the sensitivity of circular dichroism spectrum as well as enable tunable permeabilities for novel metamaterials [27–29]. In addition,

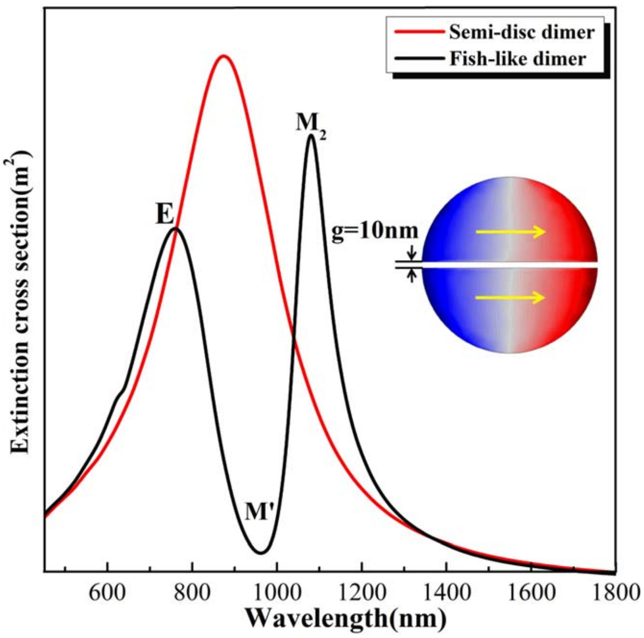

Figure 2. The extinction cross sectiones of the F-LD and semi-diac dimer nanostructure, where R1 = 145 nm, g = 10 nm and R2 = R3 = 70 nm.

magnetic effects play an significant role in many related microwave applications, such as sensing of biological applications [30], metamaterials [31], magnetic induction waveguides [32] and high resolution imaging [33]. Therefore, it is very important to design a nanostructure with adjustable multiple magnetic modes.

In this paper, a fish-like dimer (F-LD) nanostructure has been proposed. When the light incident perpendicular to the structure, the dark second-order magnetic mode can be excited. An asymmetric Fano resonance can be generated due to the coupling of the dark magnetic mode and the bright electric mode. When the nanostructure is rotated, multiple high-order magnetic plasmons can be excited. We can enhance or suppress the magnetic modes by controlling the rotation angle. In addition, when the gap shape of the dimer is changed, low-order magnetic modes can also be excited.

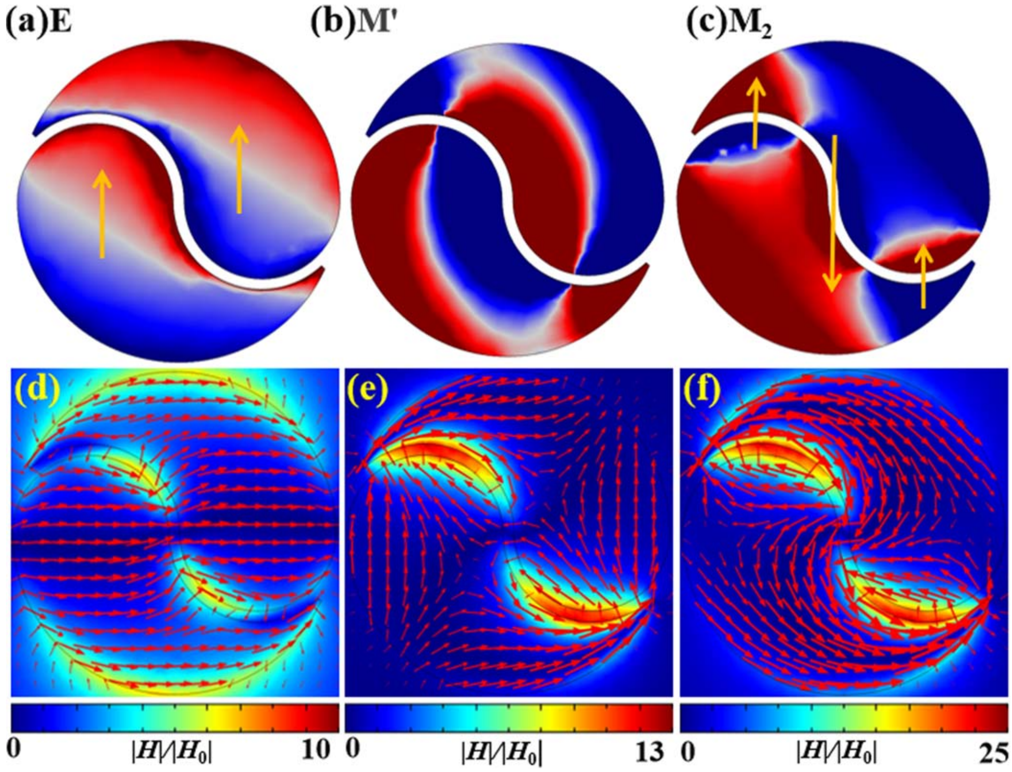

Figure 3. (a)–(c) The charge distributions of mode E, M' and dip M_2. (d)–(f) The current density and magnetic field enhancement distributions of mode E, M' and M_2. Here H represents the local magnetic field and H_0 represents the background magnetic field.

Large magnetic hot spots can be obtained with the emergence of new magnetic modes. Double Fano resonances can be generated by rotating the nanostructure or changing the gap shape, which enable our structure have great application in the field of multi-band sensing. More interestingly, when we increase the number of semi-ring contained in the gap, high even-order magnetic modes can be excited regularly and multiple Fano resonances can be observed. The generation of high even-order magnetic modes can be controled by selecting the number of semi-ring contained in the gap. This characteristic makes the structure can be well used in controllable spectral line shaping. Furthermore, the magnetic field in the gap is greatly enhanced with the generation of higher-order magnetic modes, and the maximum magnetic field enhancement can reach 49 times of the incident field, which has important application value in the field of surface enhancement spectrum.

2. Structure and simulation method

The structure of F-LD is shown in figure 1, and it is actually a disc with a s-shape gap. The materials of the nanostructure is Ag, the radius of the large disk is R1, and the radiuses of the two semi-circles are R2 and R3, respectively. In our calculations, we define m = R2 - R3 as asymmetry degree to describe the asymmetric system. The width of s-shape gap g is 10 nm and the thickness of the nanostructure T is 20 nm. The incident electromagnetic wave is perpendicular to the structure and the polarization direction is along the x-axis.

In this paper, all the calculations are completed by the finite element method (FEM). The finite element method is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. It subdivides a large problem into simple finite elements. Then, the FEM uses variational methods from the calculus of variations to approximate a solution by minimizing an associated error function. According to the finite element method, some related simulation software has been designed. In the artical, COMSOL multiphysics software package are used to do all the calculations [34]. A perfect matching layer is designed outside the structure and the structure is surrounded by air. The extinction characteristics are determined by the sum of absorption cross section and scattering cross section. The total absorption cross section is calculated by integrating the ohmic heating within the F-LD nanostructure [35]. The total scattering cross section is calculated by integrating the scattered power flux over the F-LD [35].

3. Results and discussion

3.1. The spectral properties of the F-LD nanostructure

The extinction properties of semi-disc dimer and F-LD have been shown in figure 2. The radii of semi-disc dimer and F-LD, R and R1, are 145 nm, and the gap of the two dimers g is 10 nm. It is found that there is only one resonance near 900 nm in the spectrum of the semi-disc dimer (in figure 2, red curve). The corresponding charge distribution is inserted

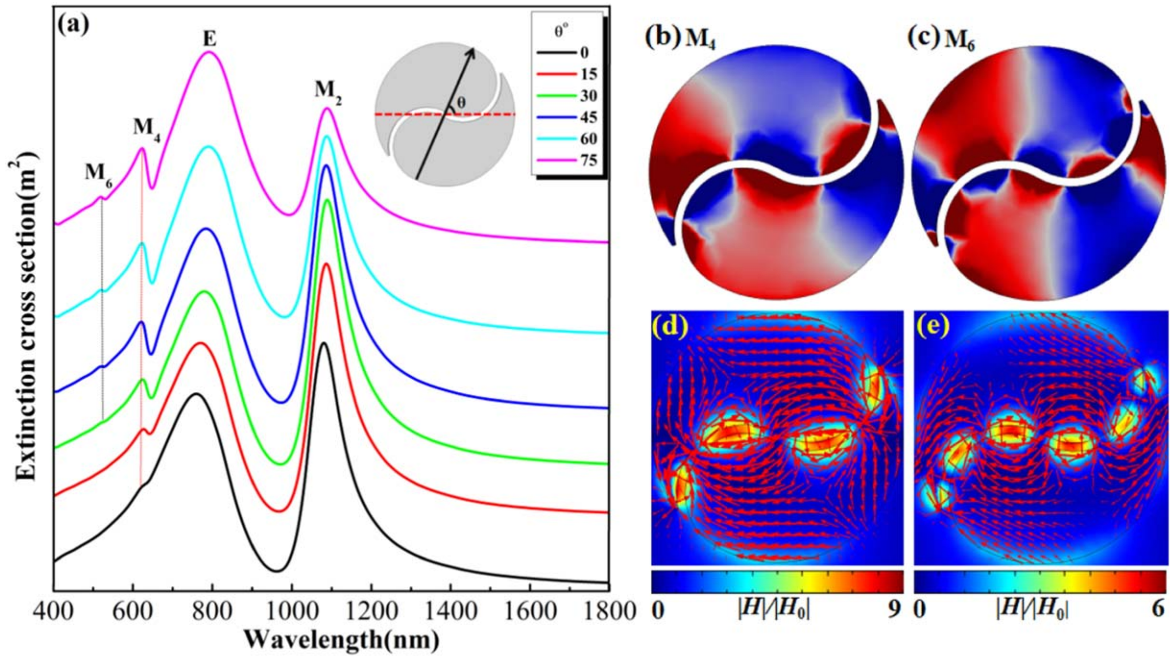

Figure 4. (a) The extinction cross section of F-LD nanostructure when it is rotated. (b), (c) The charge distributions of modes M_4, M_6. (d), (e) The current density and magnetic field enhancement distributions of modes M_4 and M_6.

in figure 2, which is a bright super-radiation mode. Compared with the extinction spectrum of semi-disc dimer, an asymmetric Fano linetype is formed between 600 and 1300 nm in the spectrum of F-LD. This indicates that the dark mode is stimulated in the F-LD due to the destruction of structural symmetry.

In order to further prove our statement, the charge, current density and magnetic field enhancement distributions at peaks and dip of the F-LD are shown in figure 3. Observing figures 3(a) and (d), it is found that the structure has a large net dipole moment at the peak near 760 nm (yellow arrow in figure 3(a)) and there is no current loop. Therefore, it is a bright electric mode, which is called mode E. For figures (c) and (f), we can see that the total electric dipole moment of the structure near 1100 nm is almost zero and two obvious current loops are formed. Therefore, it corresponds to a dark magnetic mode. We can see that the magnetic dipoles formed by two current loops are in the opposite direction, which is similar to a toroidal mode [36]. Since there are two magnetic hot spots, we call it the second-order magnetic mode, which is represented by M_2. The asymmetric Fano linetype is generated from the coupling of mode E and mode M_2. Observing the distribution of magnetic field and current density at the dip, there are two obvious current loops and the magnetic hot spots are mainly distributed in the dimer gap. Therefore, it is a magnetic Fano resonance, which we call mode M′.

3.2. Generating high-order magnetic modes and double Fano resonances through rotating nanostructure

We also study the optical properties of the structure when it is rotated. The extinction spectra are shown in figure 4(a) and the corresponding structure diagram is inserted, where θ is the angle of rotation. With the increase of θ, the original peak

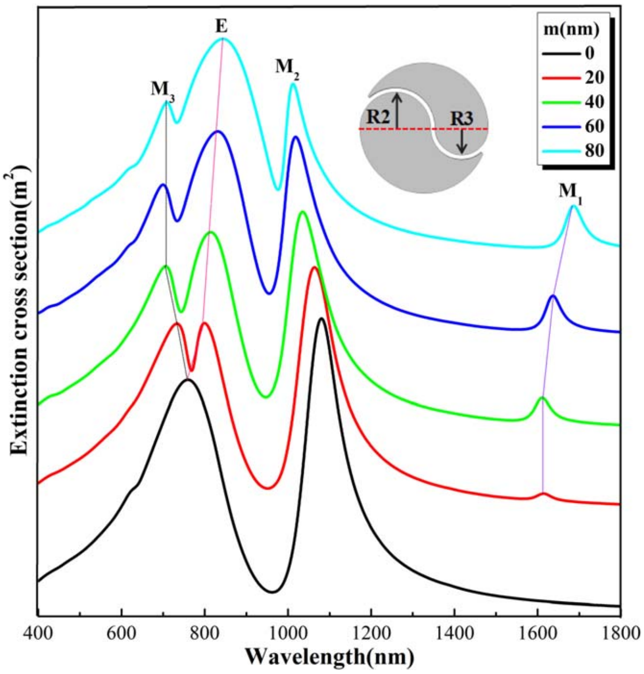

Figure 5. The extinction cross section of F-LD nanostructure by changing m.

near 600 nm becomes obvious and a new peak appears near 500 nm, we call them modes M_4 and M_6, respectively.

The charge and current density distributions of mode M_4 and M_6 are shown in figures 4(b) and (d). There are four magnetic hot spots in the gap, which are formed by four current loops respectively, and we call it the fourth order magnetic mode. Mode M_4 is a dark magnetic mode, which couples with mode E to form a new asymmetric Fano

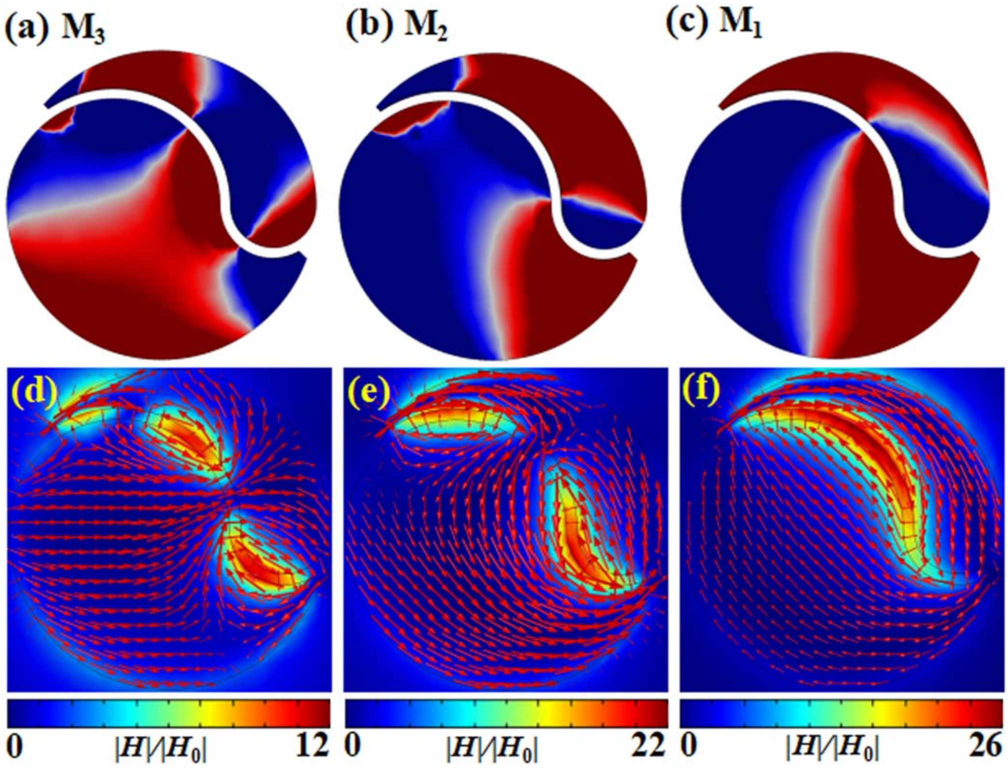

Figure 6. (a)–(c) The charge distributions of modes M_3, M_2 and M_1. (d)–(f) The current density and magnetic field enhancement distributions of modes M_3, M_2 and M_1.

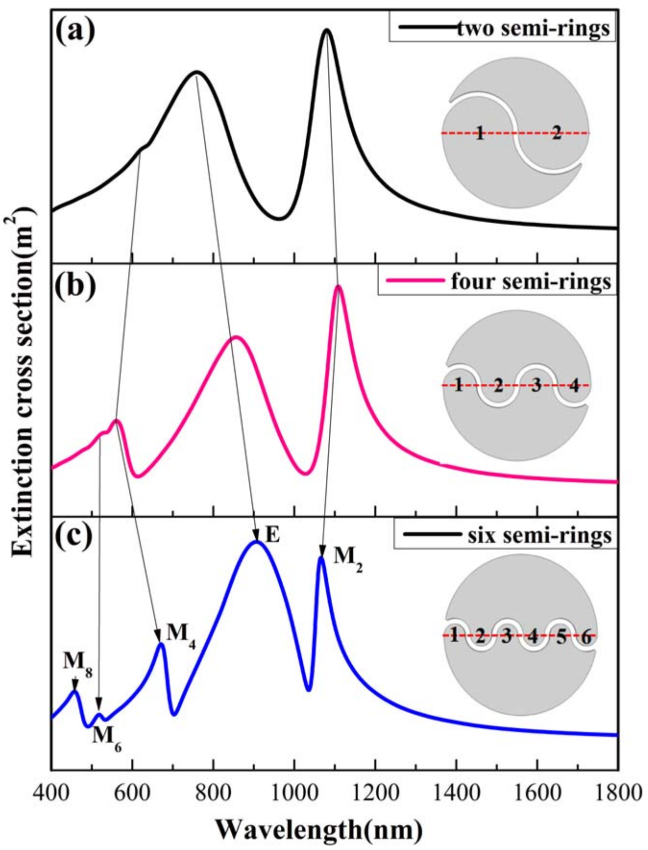

Figure 7. (a)–(c) The extinction cross section of the F-LD nanostructure when the gap with two semi-rings, four semi-rings and six semi-rings, respectively.

linetype. That is to say, with the increase of θ, double magnetic Fano resonances can be generated. Observing the distributions of charge and current density of mode M_6 in figures 4(c) and (e), it is found that six magnetic hot spots are generated, which is called six-order magnetic mode. When θ increases, the relative position between the structure gap and the polarization direction of the incident light is changed, which results in the generation of high-order modes. By rotating the structure with different angles, the generation of second, fourth and sixth order magnetic modes can be controlled conveniently. For example, when $\theta = 0°$, the second-order magnetic mode of the structure can be obtained. When $\theta > 0°$, the fourth-order magnetic mode become obvious with the increasing of θ and when $\theta > 30°$ the sixth-order magnetic mode of the structure can be obtained in the spectrum.

3.3. Generating multi-order magnetic modes and double Fano resonances by changing m

In the previous discussion, m is fixed to 0, and the sizes of R2 and R3 are both 70 nm. Now we fix the sum of R2 and R3 at 140 nm and change the value of parameter m to study the optical properties of the structure. As shown in figure 5, a new resonance appears near 1600 nm with the increase of m. In addition, the original mode E splits into two modes. In order to further study these new modes, we research the distribution of charge and current density of the structure with m = 70 nm. Figure 6(c) shows the charge distribution of the mode at 1600 nm. It is found that there is a charge node and a magnetic hot spots has been generated in figure 6(f), so it is a

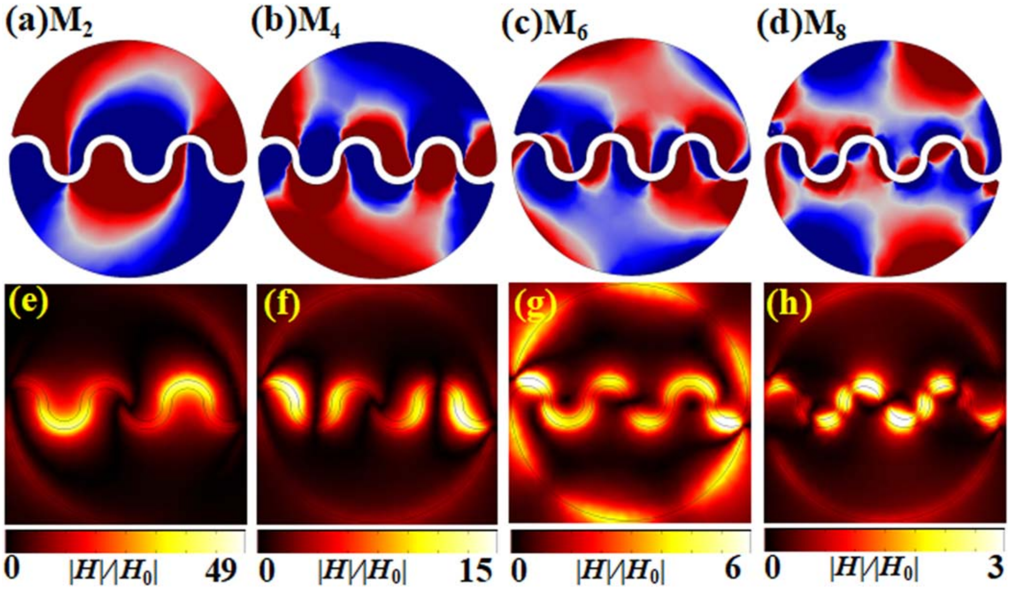

Figure 8. (a)–(d) The charge distributions and (e)–(h) The magnetic field enhancement distributions of modes M_2, M_4 , M_6 and M_8.

first-order magnetic mode, which is called M_1. Similarly, two and three magnetic hot spots can be observed in figures (e) and (d), respectively, so they are called modes M_2 and M_3. The corresponding charge distributions are shown in figures (b) and (a).

New modes M_1 and M_3 appear when m $\neq$ 0. The intensity of mode M_1 increases with the increasing of m, which is caused by the increase of structural asymmetry. However, the trend of mode M_2 is exactly the opposite of mode M_1. This is because the size difference between two fish-like structures increase with the increasing of m, which directly weakens the coupling between two parts of the dimer. The magnetic modes M_2 and M_3 are coupled to the original mode E respectively, double Fano resonances is formed in the spectrum.

Generally speaking, the second, fourth and sixth order magnetic modes can be generated by rotating the F-LD nanostructure. When m $\neq$ 0, the first, second and third order magnetic modes also can be obtained. Interestingly, at different magnetic modes, the electromagnetic field enhancement can be enhanced greatly at different areas of the gap. The emergence of multiple magnetic modes makes our structure have potential applications in high resolution imaging and sensing of biological applications.

3.4. Generation high-order magnetic modes by increasing the number of semi-rings in the gap

The gap of the dimer studied above is s shape with two semi-rings. The optical properties of the nanostructure are studied when the gap with four semi-rings and six semi-rings, and the large disc radius R1 is constant. The corresponding extinction spectra are shown in figures 7(a)–(c), in which the structure diagrams are inserted.

The extinction spectrum of F-LD structure is shown in figure 7(a), in which only mode M_2 and M_4 are excited. When the gap of the structure contains four semi-rings, we find that mode M_4 becomes more obvious and a new mode is excited around 500 nm. Since there are six magnetic hotspots in the new mode, we call it the sixth order magnetic mode, which is represented by M_6. Subsequently, the structure that the gap includes six semi-rings is also studied by us. It is found that the intensity of modes M_4 and M_6 is increased. More interestingly, another new mode is observed around 450 nm in figure 7(c). There are eight obvious hot spots in the magnetic field enhancement distribution, which is called mode M_8. This can be attributed to the coupling of the disks and cavities on both sides of the gap. When the number of semi-ring contained in the gap is increased, the numbers of coupling between disks and cavities will also increase, which leads to the regular generation of high-order magnetic modes. Therefore, we can infer that when the gap of structure includes more semi-rings, new high even-order magnetic modes will appear, then we can predict the new magnetic modes and their approximate resonance positions by changing the numbers of semi-rings contained in the gap.

To make our argument more convincing, the charge and magnetic field enhancement distribution of gap with six semi-rings are shown in figure 8. In figure 8(a), there are two charge nodes in mode M_2. Correspondingly, there are two magnetic hot spots in the magnetic field enhancement diagram. Similarly, we can observe four, six and eight magnetic hot spots in figures 8(f)–(h), which correspond well to the four, six and eight nodes in figures 8(b)–(d). In summary, high even-order magnetic modes can be excited regularly by increasing the number of semi-ring contained in the gap.

At the same time, multiple Fano resonances can be generated. Based on this optical property, we can not only modulate the spectrum in multiple bands simultaneously, but also achieve controllable spectral line shaping, which is of great significance for the application of multi-band sensing. In addition, the magnetic field is enhanced greatly in most areas of the gap, and the maximum magnetic enhancement is 49 times that of the incident field, which makes our structure have important application value in surface enhanced spectroscopy.

4. Conclusion

In summary, a F-LD nanostructure has been studied in this paper. The dark second order magnetic mode is excited due to the coupling between two parts of the dimer, which couples with the bright electrical mode to produce an asymmetric Fano linetype. When the structure is rotated or the value of parameter m is changed, the first, second, third, fourth and sixth order magnetic modes can be excited in the spectrum, and the plasmonic double magnetic Fano resonances is generated. In addition, when we increase the numbers of semi-rings contained in the gap while maintaining other parameters unchanged, the high even-order magnetic modes can be excited regularly. At the same time, the magnetic field in the gap is greatly enhanced, and the maximum magnetic field enhancement is 49 times that of the incident field. The generation of multi-order magnetic modes and their maximum field enhancement make it have potential applications in improving the sensitivity of circular dichroism spectroscopy and surface-enhanced spectroscopy.

Acknowledgments

This work was supported by the National Natural Foundation of China (Grant No. 11604198)

ORCID iDs

Yiping Huo https://orcid.org/0000-0002-0013-9593

References

[1] Barnes W L, Dereux A and Ebbesen T W 2003 Surface plasmon subwavelength optics *Nature* **424** 824
[2] Saïd B *et al* 2016 Fano-like resonance emerging from magnetic and electric plasmon mode coupling in small arrays of gold particles *Sci. Rep.* **6** 32061
[3] Zhang Q, Wen X L, Li G Y, Ruan Q F, Wang J F and Xiong Q H 2013 Multiple magnetic mode-based fano resonance in split-ring resonator/disk nanocavities *ACS Nano* **7** 11071–8
[4] Lal S, Link S and Halas N J 2007 Nano-optics from sensing to waveguiding *Nat. Photonics* **1** 641–8
[5] Schuller J A, Barnard E S, Cai W, Jun Y C, White J S and Brongersma M L 2010 Plasmonics for extreme light concentration and manipulation *Nat. Mater.* **9** 193–204
[6] Noginov M A, Zhu G, Belgrave A M, Bakker R, Shalaev V M, Narimanov E E, Stout S, Herz E and Suteewong T 2009 Wiesner U demonstration of a spaser-based nanolaser *Nature* **460** 1110–2
[7] Liu W and Kivshar Y S 2018 Generalized Kerker effects in nanophotonics and meta-optics *Opt. Express* **26** 13085
[8] Breton J C L 2011 Spin precession and inverted Hanle effect in a semiconductor near a finite-roughness ferromagnetic interface *Phys. Rev. B: Condens* **84** 054410
[9] Li J *et al* 2014 Higher order fano resonances and electric field enhancements in disk-ring plasmonic nanostructures with double symmetry breaking *Plasmonics* **9** 1439–45
[10] Fu Y H *et al* 2012 Generating and manipulating higher order fano resonances in dual-disk ring plasmonic nanostructures *ACS Nano* **6** 5130–7
[11] Francescato Y, Giannini V and Maier S A 2012 Plasmonic systems unveiled by fano resonances *ACS Nano* **6** 1830–8
[12] Wang L *et al* 2016 Analysis of symmetry breaking configurations in metal nanocavities: identification of resonances for generating high-order magnetic modes and multiple tunable magnetic- electric Fano resonances generation *J Appl.Phys.* **119** 1685–706
[13] Thyagarajan K, Jérémy B and Martin O J F 2013 Augmenting second harmonic generation using fano resonances in plasmonic systems *Nano Lett.* **13** 130402103354004
[14] Hao F *et al* 2009 Tunability of subradiant dipolar and fano-type plasmon resonances in metallic ring/disk cavities: implications for nanoscale optical sensing *Acs Nano* **3** 643–52
[15] Ahmadivand A, Sinha R and Pala N 2015 Hybridized plasmon resonant modes in molecular metallodielectric quad-triangles nanoantenna *Opt. Commun.* **355** 103–8
[16] Naseer M *et al* 2017 Plasmonic spectral splitting in ring/rod metasurface *Nanomaterials* **7** 397
[17] Watanabe K *et al* 2018 Plasmonic properties of gold nanoparticle clusters formed via applying AC electric field *Soft Matter* **10** 1039
[18] Zhang J *et al* 2018 An engineered CARS substrate with giant field enhancement in crisscross dimer nanostructure *Sci. Rep* **8** 740
[19] Miroshnichenko A, Flach S and Kivshar Y 2010 Fano resonances in nanoscale structures *Rev. Mod. Phys.* **82** 2257–98
[20] Artur C G *et al* 2018 Plasmonic nanoparticle-based expansion microscopy with surface-enhanced Raman and dark-field spectroscopic imaging *Biomed. Opt. Express* **9** 603
[21] Kazemi-Zanjani N *et al* 2018 Multiwavelength surface-enhanced raman spectroscopy using rainbow trapping in width-graded plasmonic gratings *Adv. Opt. Mater.* **6** 1701136
[22] Amin M, Ramzan R and Siddiqui O 2017 Fano resonance based ultra high-contrast electromagnetic switch *Appl. Phys. Lett.* **110** 181904
[23] Kobayashi K *et al* 2002 Tuning of the fano effect through a quantum dot in an aharonov–bohm interferometer *Phys. Rev. Lett.* **88** 256806
[24] Qin J *et al* 2019 Phenylboronic acid-functionalized ultra-pH-sensitive micelles for enhanced tumor penetration and inhibition *in vitro J. Mater. Sci.* **54** 5695–711
[25] Emami-Nejad H and Mir A 2017 Design and simulation of a flexible and ultra-sensitive biosensor based on frequency selective surface in the microwave range *Opt. Quantum Electron.* **49** 320
[26] Yi Z, Niu G and Chen J F 2016 Dipole, quadrupole, and octupole plasmon resonance modes in Ag nanoring structure: local field enhancement in the visible and near infrared regions *Plasmonics* **11** 37–44
[27] Scholl J A *et al* 2015 Evolution of plasmonic metamolecule modes in the quantum tunneling regime *ACS Nano* **10** 1346
[28] García-Etxarri A and Dionne J A 2013 Surface-enhanced circular dichroism spectroscopy mediated by nonchiral nanoantennas *Phys. Rev.* B **87** 235409
[29] Fan Z, Zhang H and Govorov A O 2013 Optical properties of chiral plasmonic tetramers: circular dichroism and multipole effects *J. Phys. Chem.* C **117** 14770–7
[30] Maduraiveeran G, Sasidharan M and Ganesan V 2018 Electrochemical sensor and biosensor platforms based on

advanced nanomaterials for biological and biomedical applications *Biosens. Bioelectron.* **103** 113

[31] Vestler D *et al* 2018 Circular dichroism enhancement in plasmonic nanorod metamaterials *Opt. Express* **26** 17841

[32] Izdebskaya Y *et al* 2017 Magnetic routing of light-induced waveguides *Nat. Commun.* **8** 14452

[33] Aasen H and Bolten A 2018 Multi-temporal high-resolution imaging spectroscopy with hyperspectral 2D imagers—from theory to application *Remote Sens. Environ.* **205** 374–89

[34] Jianming J 2002 *The Finite Element Method in Electromagnetics* 2nd edn (New York: Wiley) p 75 (mathscinet.ams.org/mathscinet-getitem?mr=1903357)

[35] Li Y *et al* 2017 Generation and manipulation of multiple magnetic fano resonances in split ring-perfect ring nanostructure *Plasmonics* **12** 1613–9

[36] Zhong-Jian Y, Qian Z and Jun H 2019 Fano interferences of electromagnetic modes in dielectric nanoblock dimers *J. Appl. Phys.* **125** 063103