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Higher order fano resonances in plasmonic nanostructures with two disks outside one ring

W Qu[1], J Li[1,*], X Y Wang[1] ,T Tao[2] and C L Zhu[3]

[1] Department of Precision Machinery and Precision Instrumentation, University of Science and Technology of China, Hefei, 230027, China
[2] Academy of Opto-Electronics, Chinese Academy of Sciences, Beijing, 100094, China
[3] School of Electronic and Information Engineering, Hefei Normal University, Hefei , 230601, China

Corresponding author and e-mail: J Li, lijing@ustc.edu.cn

Abstract. A kind of plasmonic nanostructure with two disks placed outside a ring is introduced. When incident light is perpendicular to the surface of the structure, the extinction spectra in the observed wavelength range show that octupolar modes are reduced as the radii of two-disks are different. In the case of two disks with the same size symmetrically around the ring (the SDDR structure), octupolar modes are suppressed absolutely. For SDDR structure, the larger the size ratios of the ring to the disks, the easier higher order dark modes in the ring are excited; as higher order resonances appear, lower order resonances are reduced. The decapolar mode of the SDDR structure with the ring radius of 250nm and two-disk radius of 60nm is in the near-infrared wavelength region, its contrast ratio (CR) and figure of merit (FOM) can reach 87% and 22.5, respectively, which demonstrates application potentials for high-performance biochemical sensing.

1. Introduction

Fano resonances arise from the coherent interference of broad bright modes and narrow dark modes [1-5]. Due to their spectral tunability, attainable field enhancement, and refractive index sensitivity, there are widespread interests in the realization of Fano-type interference phenomenon [6-10]. Advances in nanofabrication, nano-optical characterization, and the improvements in computer simulation technology have led to the emergence of various nanostructures which can generate Fano resonances [11-15].

Disk/ring nanostructures are usually chosen as the fundamental plasmonic structures. The ring provides higher order resonance modes (narrow dark modes), which are induced by the disk dipolar mode (broad bright mode) and coupled with it [16-18]. Fu et al. designed dual-disk ring nanostructures (with two disks inside one ring) to study the generation and tunability of higher order Fano resonances [19-20]. The CR(contrast ratio) and FOM(figure of merit) of the triakontadipolar Fano resonance in the symmetric dual-disk ring (SDDR) nanostructures can reach 57% and 17, respectively. Zhang et al. reported a disk-ring nanostructure with a disk outside a ring [21]. They found that compared with the structure of a disk inside a ring, the structure has larger field enhancement, stronger intensity of higher order Fano resonances. However, it has lower FOM in sensing application. We utilize the advantages

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of each structure and propose a new disk/ring nanostructure with two disks outside a central ring for generating higher order Fano resonances. We change the outer radius of the ring and the disk radius in the nanostructure to tune the higher order Fano resonance. To evaluate the sensing performance of the nanostructures, the CR [22] and FOM are used [23-24]. The finite difference time domain method (FDTD) is used to compute the spectra and electric field distribution.

2. Results

Figure 1 illustrates the geometry composed of two disks and one ring. Two disks are located outside the ring, and their centers are on a line. The gap (d=10nm), the thickness of metal layer (h=30nm), and the ring width (w=20nm) are fixed. The ring radius r and the radii of the disks r1 and r2 are changed for study. The material used in all of plasmonic nanostructures is a weakly dissipating metal, silver, which is effective in the excitation of higher order resonances [25-26]. The incident light is normal to the metal surface with the polarization parallel to the gap. The experimentally measured silver permittivity data [27] are used in simulations, and the structures are deposited on the glass (n=1.456).The extinction spectra are obtained as the sum of the absorption and scattering spectra.

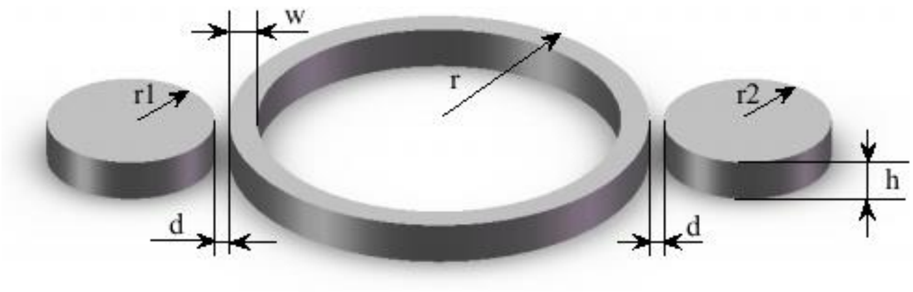

Figure 1. Geometry of the two-disk ring with fixed parameters: w =20nm,d=10nm, h=30nm, and various r1 , r2 and r.

When incident light irradiates the structure, the bright dipolar mode is excited both in the disks and ring. The dark multipolar modes in the ring are excited by the dipolar disk mode due to near-field coupling, which cannot be excited directly by light at normal incidence [28]. The coupling of the multipolar ring modes with the broad dipolar disk mode generates higher order Fano resonances.

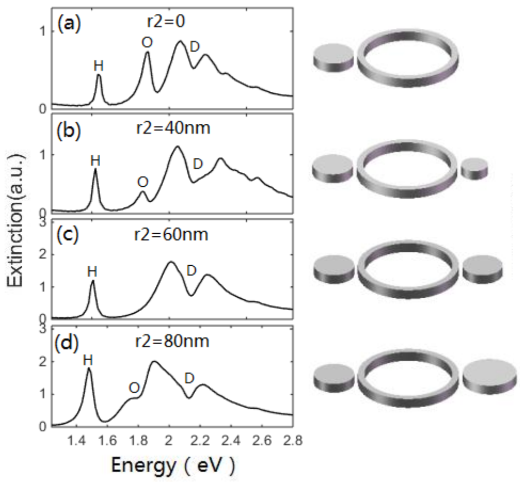

Figure 2. Extinction spectra of structures with various r2 from 0 to 80nm. The letters "H", "O", and "D" represent hexapolar, octupolar, and decapolar Fano resonances, respectively.

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Figure 2 exhibits the structures with various r2 from 0 to 80nm, the r1 and r are fixed (r1=60nm, r=150nm). As r2 increases from 0 to 60nm, the hexapolar and decapolar are enhanced, while the octupolar mode is reduced. When the size of the right disk r2 is equal to 60nm, the structure becomes symmetric dual-disk ring structure (SDDR), as shown in Figure 2(c); the octupolar mode is absolutely suppressed, and only hexapolar (1.51eV) and decapolar(2.15eV) modes exist in spectra, which is caused by the two in the same phase oscillating disks [21] When r2 increases to 80nm, the octupolar mode reappears. Obviously, the asymmetric disk leads to the appearance of the octupolar mode.

Figure 3(a) shows the extinction spectra of the symmetric dual-disk ring structure (SDDR) with fixed parameters (r=150nm) and various disk radii r1, r2 (r1=r2). It can be seen that as the radii of disks increase from 40 to 80nm, the hexapolar resonance peak is enhanced obviously, while the decapolar resonance is reduced; the dipolar hybridization mode redshifts, and thus, resulting in a slight redshift of the hexapolar and decapolar Fano resonances. In Figure 3(b), we fix the size of two disks (r1=r2=60nm) and change the outer radius of the ring r from 50 to 250nm. When r=50nm, no Fano resonance appears, as the ring has similar size with the disks and dark modes in the ring are difficult to be excited. When the radius of the ring is equal to or larger than 100nm, higher order resonances occur. The hexapolar resonance is weakened and higher order Fano resonances redshift significantly as the radius of the ring increases. In these two cases, the larger the size ratios of the ring to the disks, the easier higher order dark modes in the ring are excited. In addition, as higher order resonances appear, the lower order resonances are reduced.

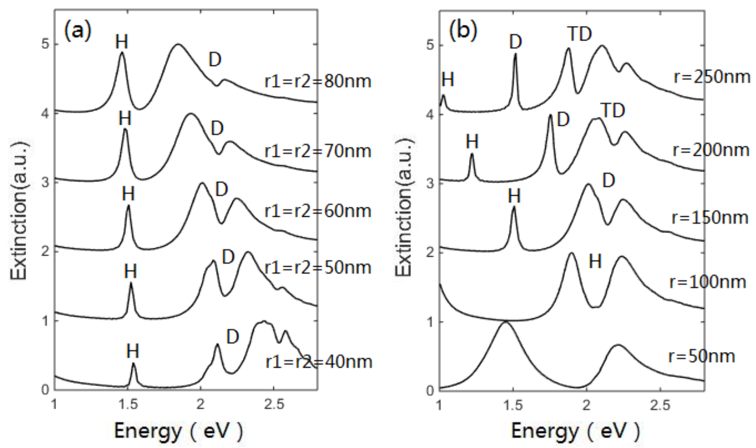

Figure 3. Extinction spectra of (a) structures with various radii of disks (from 40nm to 80nm),and (b) structures with various radii of ring (from 50nm to 250nm).The letters "H", "D", and "TD" represent hexapolar, decapolar and tetradecapolar Fano resonances, respectively.

In the SDDR structure with r=250nm, r1=r2=60nm, the extinction spectra of the decapolar (D mode) and tetradecapolar (TD mode) Fano resonances appear at 1.51 and 1.87eV, respectively, shown in Figure 3(b), and the decapolar Fano resonance is in the near-infrared wavelength range. The corresponding distributions of electric field of these modes are shown in Figure 4(a) and (b), respectively. They have ten and fourteen nodes at the ring wall, respectively, and every node is a charge habitat.

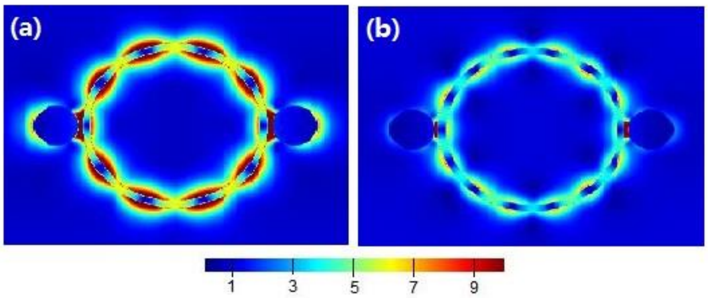

Figure 4. Distributions of electric field amplitudes at the decapolar (a) and tetradecapolar (b) modes of the SDDR structure with r=250nm, r1=r2=60nm, respectively.

We use the contrast ratio (CR) and the figure of merit (FOM) to evaluate the sensing performance of higher order Fano resonances generated in the SDDR structure with r=250nm, r1=r2=60nm. CR is defined as the ratio of the difference between the peak and the dip value to the sum of these two values. The FOM is defined as the ratio of the sensitivity of the surrounding medium to the line width of the resonance. The structures are surrounded by different media with refractive indices1.00, 1.33, 1.42, and 1.56. Figure 5(a) shows that the decapolar (D mode) and tetradecapolar (TD mode) Fano resonances redshift significantly with the increase of the refractive index of the surrounding medium n. Figure 5(b) demonstrates the linear plot of the shifts of the Fano resonances versus the refractive index of the medium. In the structure, the sensitivity, the CR, and the FOM of the D mode are 0.58eV RIU^{-1}, 87%, and 22.5, respectively, and the corresponding values of the TD mode are 0.72eV RIU^{-1}, 44%, and 11, respectively. High values both in CR and FOM of the D mode in the SDDR structures demonstrate great sensitive performance, showing the potential applications as chemical and biological sensors [29-30].

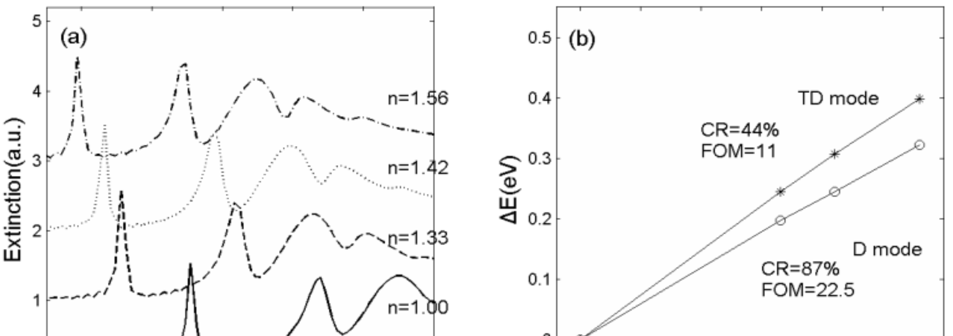

Figure 5. (a) Extinction spectra of the decapolar and tetradecapolar Fano resonances of the SDDR structure. The refractive indexes of the surrounding media are 1.00, 1.33, 1.42, and 1.56. (b) Spectral shifts of the Fano resonances as a function of the refractive index with the decapolar and the tetradecapolar Fano resonances. The corresponding values of the FOM and CR are shown in the plots.

3. Conclusions

In this article, we have studied the generation of higher order Fano resonances in the structure with two disks outside one ring under normal incidence. We compare the extinction spectra of the

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structures with various r2 from 0 to 80nm and find that the SDDR structures have less but stronger resonance modes, and the octupolar modes are suppressed in the observed energy region. In the SDDR structure, the larger the size ratios of the ring to the disks, the easier higher order dark modes in the ring are excited; as higher order resonances appear, the lower order resonances are reduced. In the SDDR structure with the ring radius of 250nm and two-disk radius of 60nm, the CR and FOM of the decapolar mode can reach 87% and 22.5, respectively. These optical characters of the designed nanostructures can provide a promising platform for biochemical sensing.

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