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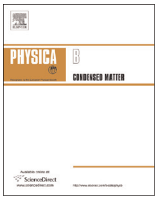

Asymmetric split nanorings for Fano induced plasmonic sensor in visible region

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ABSTRACT

Fano resonance exhibits high sensitivity and promising applications in the field of ultra-sensitive plasmonic sensor. In this work, the Fano lineshape in spectra of gold rectangular split nanorings (RSNRs) is investigated using the finite element method. The simulation results figure out the Fano lineshape could be modulated by the positions of split gap in RSNRs for symmetry breaking, which is explained by the plasmonic hybridization theory. Furthermore, the high order bonding plasmon mode H in absorption spectra exhibits high sensitivity in visible region. Our investigations here are beneficial for the design and application of ultra-sensitive LSPR sensor in visible region.

1. Introduction

Due to the amazing ability of manipulating light under sub-wavelength, plasmonics has attracted more and more attentions all over the world in the last twenty years [1,2]. The charge density wave at metal material surface caused by coupling between collective oscillation of free electrons and photon is called surface plasmon polaritons (SPPs). The existence of SPPs bound the electromagnetic (EM) field near the material surface (metal, *etc.*) that the energy of EM field decays exponentially in the normal direction of surface and tightly confined at the curved location. This fantastic property could generate hugely enhanced EM field near the material surface and also could realize optical waveguide in sub-wavelength, which are intensively applied in the fields of surface enhanced spectra [3–7], photovoltaic[8,9], photocatalysis [10–12], nano-optics [13–15], ultra-transmission [16], nonlinear optics [17,18],*etc.*

One of the most interesting applications is the sensor based on localized surface plasmon resonance (LSPR) [19–23], the extremely strong oscillation of SPPs. Several resonance frequencies could usually be obtained in the visible region for different excitations of SPP modes (dipole mode, quadrupole mode, *etc.*) in the same nanostructure. The SPR frequencies in optical spectra are intimately related to plasmonic nanostructure's local dielectric environment such as the concentration of the solvent and also the configuration of the absorbed molecule. Therefore, based on the optical spectra, LSPR sensor is able to monitor the minimal variation of ambient environment and extensively applied in chemical and bioscience. Recently, a much more sensitive sensor based on plasmonic Fano resonance has been reported [24–29], which also worked through optical spectra. In a complex plasmonic structure consisting of closely placed simple elements, the primitive plasmonic modes of the elements interact and form hybridized bonding and antibonding plasmonic modes ("bright" and "dark" modes). The former one with finite dipole moment could be efficiently excited by light and the latter one with zero dipole moment could not. A typical plasmonic Fano resonance is generated by the coupling and interference of dark mode with narrow resonant band and bright mode with broad resonant band. Benefiting from the interference phenomenon, the great higher sensitive level of Fano sensor has been achieved compared to the LSPR sensor that relies on the primitive SPP modes [30,31]. Since the coherent coupling of different SPP modes could be modulated by the symmetry breaking [32], the Fano lineshapes of asymmetric plasmonic nanostructures is of great interest to many researchers such as the plasmonic nanoclusters [24,26], metallic nanodisk [32], ring/crescent-ring [33], which have been used to tune the Fano profile for sensing. The previous studies on the asymmetric gold split nanorings indicated that it exhibited good optical sensing properties at low frequency, mainly from the near-infrared to terahertz region [34–36]. In this work, the plasmonic Fano lineshape of asymmetric gold rectangular split nanorings (RSNRs) is studied using finite element method (FEM). Firstly, the charge

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distribution and transmission spectra of half RSNRs are investigated. Secondly, the transmission spectra of the whole RSNRs are analyzed and understood by plasmonic hybridization theory. Thirdly, the Fano lineshape in transmission spectra of RSNRs are discussed and modulated by the symmetry breaking, the position of gap in RSNRs. Lastly, the sensitivity of an asymmetric RSNRs sensor has been estimated.

2. Numerical simulation

In this work, all results are obtained by FEM simulation (COMSOL 4.3a commercial package). The gold RSNRs are rectangular nanorings which are separated by splits of 20 nm wide, and placed on a quartz substrate. Fig. 1(a) shows the dimensions of gold RSNRs in x–y plane in a unit with a periodic boundary. With polarization parallel to x axis, the incident light propagates from the top along the z axis through air, whose amplitude of electric field is 1 V/m and input power density is 0.28 mW/μm^2. The period (T) and the thickness (t) of RSNRs were 600 nm and 55 nm, respectively and the length of horizontal arms (d) could vary from 0 nm to 50 nm. Fig. 1(b) shows transmission spectrum of an asymmetric RSNRs ($d=20$ nm) in the medium with a refractive index $n=1.33$. There are obviously two peaks in the spectrum, one in visible region (the high order bonding mode H) while the other in near Infrared region (the bonding mode D).

3. Results and discussions

For a complex nanostructure consisting of two neighboring half RSNRs, the plasmonic properties of the whole one are dominated by the interaction between SPP modes of the two elements. Therefore, we firstly investigated the individual half RSNRs with various lengths of horizontal arms. Because of symmetric structure, the results of both left and right part half RSNR remains the same while the polarization of incident light is horizontal (along the x axis as is shown in Fig. 1(a)). In this case, we focus on the right part of RSNRs whose transmission spectra are shown in Fig. 2 (wavelength varied from 500 nm to 1200 nm). There are three peaks that we concern in the spectra which are represented by numbers respectively ("1", "2" and "3" in Fig. 2 respectively). The dash line indicates the variation tendency of the three peaks as the length of horizontal arm increased (d varys from 0 nm to 100 nm). It is clearly shown that both peaks 1 and 3 have a redshift while peak 2 (actually an inflection) remaines fixed (and in some condition disappears). To understand those phenomena, the surface charge distribution of three peaks with the longest horizontal arm ($d=100$ nm) are illustrated in Fig. 2(c). The spectra in Fig. 2 (b) suggest that the deep peak 3 (blue dotted line) doesn't clearly turn up until $d>=30$ nm with a redshift from 660 nm to 850 nm. This is because peak 3 is produced from the plasmonic resonance of dipole modes in two horizontal arms (illustration 3), which reduces the resonance frequency while the collective oscillation length is smaller. When d is smaller than 30 nm, the half RSNR is much more like a rod in the lateral mode. Then the intensities of peak 1 (red dotted line) and peak 2 (black dotted line) are weak and the shapes become flat in a large area of spectra in Fig. 2(a). Peak 1 is generated from plasmonic resonance of coupling of the two horizontal arms and the vertical arm when they have an opposite dipole momentum as shown by the illustration 1. As the horizontal arms become longer, the peak shifts to red. Peak 2 actually is the high order excitation of the arm cuboid [30] (Fig. 2 (c) illustration 2) which behaves as a dark mode so that we do not see it since peak 1 or peak 3 overlaps with it. From the surface charge distribution we can see that on the cross section of the horizontal arms, the charge in the middle is opposite from the corner. The opposite momentum of the charge oscillation in the direction normal to the substrate makes it 'dark'. And the oscillation length is always the thickness of the nanoring, so the peak position keeps the same. When peak 1 shifts and overlaps with it, there would be a Fano shape shows up ($d>=70$ nm) and the same as the peak 3 overlaps with it ($d=20$ nm and 30 nm).

Based on the results of half RSNRs, the plasmonic hybridization theory is used to analyze the spectrum of the whole RSNR. The transmission spectra in Fig. 3 indicates that the hybridization process of a whole RSNR consists of two half RSNRs ($d=40$ nm and 60 nm respectively). As we discussed above, when the two halves of RSNRs are considered together, due to the strong coupling, the modes of the original half RSNRs hybridized and formed new modes shown in Fig. 3. The coupling of main dipole mode (the main peak in Fig. 2(b)) of the half RSNRs splits into two peaks because of the bonding (D mode also indicated in Fig. 1(b)) and antibonding modes shown in Fig. 3(b). The surface charge distribution in the inset of Fig. 3(b) clearly confirms the dipole oscillation of the modes. Since the structure is not symmetric, the anti-bonding mode is not totally 'dark', but shows a small shoulder. The coupling of the mode in Fig. 2 (peak 1) shows a broad peak at high energy. As the original peak is very broad, we can't distinguish the bonding and anti-bonding modes. However, according to the surface charge distribution, it is a bonding mode (the high order bonding mode H also indicated in Fig. 1(b)) at the

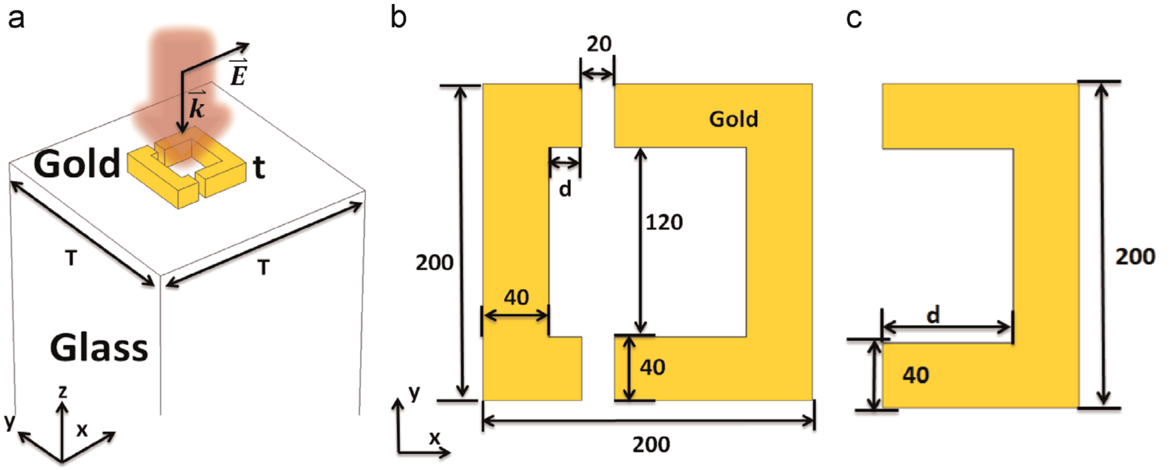

Fig. 1. (a) Dimensions of gold RSNRs in x–y plane with the unit in nm. (b) The transmission spectrum of an asymmetric RSNRs in figure (a) ($d=20$ nm) in medium with a refractive index $n=1.33$.