Dual-Fano resonances and sensing properties in the crossed ring-shaped metasurface

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Abstract

We study dual-Fano resonances and its sensing properties in a crossed ring-shaped metasurface by use of the finite-different time-domain (FDTD) simulation. The results show that the dual-Fano resonances in the proposed crossed ring-shaped metasurface are caused by the interaction among three local surface plasmon resonances (LSPRs), and the spectra of dual-Fano resonances can be tuned by the radius of the circular ring (CR) nanostructure, the distance between the center of the two CRs in x direction, and the polarization of the incident light. Interestingly, single Fano resonance splits into dual-Fano resonances in the case of asymmetric ring structure arrangement or non-y-axis polarized incident or the distance $d < 120$ nm. Moreover, we can also find that the refractive sensitivity in the proposed crossed ring-shaped metasurface can reach up to 1010 nm/RIU and 1300 nm/RIU at Fano resonance peak 1 and Fano resonance peak 2, respectively. These results may play an important role for designing high sensitive plasmonic sensors.

1. Introduction

Local surface plasmon resonance (LSPR) is the collective oscillation of electrons excited by the incident light, which is confined at the surface of the metal nanoparticle [1–3]. The interaction among the different LSPRs on the adjacent nanoparticles can form the new normal modes on the surface of the nanoparticles, so many interesting phenomenon are observed based on the coupling between plasmonic resonance modes, such as plasmon induced transparency [4–10], Fano resonance [13–16], extraordinary optical transmission [17, 18], breaking the optical diffraction limit [19, 20], and so on. These peculiar optical phenomenon are widely used in surface-enhanced spectroscopies [21, 22], biochemical sensors [23, 24], plasmonic switching [25, 26], plasmonic filter [27, 28], plasmonic absorber [29–35], and so on.

Fano resonance has the asymmetrical spectra caused by the interaction between the continuous mode and discrete mode [36, 37], the sharp spectra of Fano resonance makes the strong dispersion appearing at the wavelength of Fano resonance. Thus, Fano resonance is widely used in enhancing sensing, light field enhancement, optical storage, and so on [38–40]. And Fano resonance is studied in a variety of structure, such as metallic waveguides [41, 42], dielectric waveguides [43, 44], optical gratings [45, 46], graphene systems [47–48], and so on. There are also many kinds of metasurface, which can also achieve Fano resonance, such as single nanodisk, dimer and multiparticle oligomers. For the single nanodisk nanostructure, Fano resonance is often caused by introducing arranged defects, such as narrow split gap, cut-out wedge, and so on [49, 50]. For dimer and multiparticle oligomers structures, Fano resonance is always caused by the interaction among the closely adjacent metallic nanoparticles in different size or shape [51, 52]. Nordlander et al. discussed the typical Fano resonance in plasmonic metamaterials [53]. Singh et al. investigated high-Q Fano resonance with the high sensitive sensors in metamaterials [54]. Li et al. discussed conventional plasmonic sensors and slow-light sensors based on Fano resonance in the resonator coupled waveguide [55]. Tang et al. studied Fano resonance with high sensitivity sensing in graphene coupled systems [56]. Liu et al. reported Fano resonance and its sensing performance in the pure dielectric metasurface [57]. However, there are few works about Fano resonance and its sensing

properties in the crossed nanostructure metasurface. Different from single nanodisk, separated dimer and multiparticle, the crossed metasurface can form more possible plasmonic resonance modes, so multiple Fano resonances can be achieved in the simple crossed nanostructure metasurface.

In this paper, we proposed a crossed ring-shaped metasurface, and dual-Fano resonances and high sensitivity sensing are also discussed in the proposed metasurface through FDTD simulation method. We find that the dual-Fano resonances can be effectively tuned by the radius of the CR nanostructure, the distance between the center of the two CRs in x and y directions, and the polarization of the incident light. Especially, single Fano resonance splits into dual-Fano resonances through adjusting structural parameters and polarization directions. What is more, the maximum of sensitivity $\text{Max}[s] = 1010 \text{ nm/RIU}$ and $\text{Max}[s] = 1300 \text{ nm/RIU}$ for Fano resonance peak 1 and Fano resonance peak 2 are observed in the proposed crossed ring-shaped metasurface. These research results may play important roles for designing ultra-high sensitive sensors.

2. Structure Model And Simulation Method

We propose a crossed ring-shaped metasurface as shown in Fig. 1. The metal is chosen to be Au, and the substrate is SiO_2 , the permittivity of Au and SiO_2 reference to the reported articles [58–60]. Figure 1(a) shows the schematic diagram of the proposed crossed ring-shaped metasurface, and Fig. 1(b) shows the x-y plane view of the proposed metasurface. $P_x = P_y = 400 \text{ nm}$ are the length of each cell in x and y directions, respectively. $r_{1\text{in}} = 75 \text{ nm}$ and $r_{1\text{out}} = 100 \text{ nm}$ are the inside radius and outside radius for the left RC structure, respectively. $r_{2\text{in}}$ and $r_{2\text{out}}$ are the inside radius and outside radius for the right RC structure, respectively. d is the distance between the center of the proposed two RCs in x direction. The transmission spectra of the proposed crossed ring-shaped metasurface is simulated by use of FDTD simulation method. In our simulation process, the effective area is divided into uniform Yee cells with $\Delta x = \Delta y = \Delta z = 1 \text{ nm}$ and the $\Delta t = \Delta x/2c$, where c is the velocity of light in vacuum [61, 62], and the perfectly matched layer (PML) is chosen in this numerical simulation process [63–65]. The Gaussian beam incidents from the positive direction of z axis in our simulation.

Figure 1. (a) Schematic diagram of the crossed ring-shaped metasurface, (b) x-y plane view of the proposed crossed ring-shaped metasurface.

3. Results And Discussions

Firstly, we investigate the transmission responses of the proposed crossed ring-shaped metasurface when the polarization of the incident light is x direction as depicted in Fig. 2 (a). We can see that a transmission dip appears at the wavelength of 994.2 nm (red line) when there is only left CR nanostructure arranged on the substrate. The transmission dip is caused by LSPR on the surface of left CR. The other transmission dip appears at the wavelength of 1023 nm (black line), which is caused by LSPR on the right CR. Interestingly, double Fano resonances can be observed (blue line) when the left and right CRs are arranged on the substrate as shown in Fig. 2(a). Different from the separated dimer and

multiparticle metasurface, the crossed metasurface can form more possible plasmonic resonance modes, so multiple Fano resonances can be achieved in this simple crossed metasurface. Then we study the electric field distribution E_z as shown in Fig. 2(b)-2(e). Figure 2(b) shows the electric field distribution E_z at the wavelength of 994.2 nm when there is only right CR configured on the substrate, we can see that the strongly confined electric field at the right CR. The same as Fig. 2(b), Fig. 2(c) shows confined electric field at the left CR. Thus, the obvious transmission dips can be observed in Fig. 2(a). Then we describe the electric field distribution E_z at the wavelength of Fano resonance peaks. We can see that the opposite electric field distribution are shown in Fig. 2(d) and 2(e). The additional LSPR appears at the middle of structure when the two CRs are crossed with each other, so the left Fano resonance is caused by the interaction between the additional LSPR at the middle structure and LSPR at the right CR. However, the right Fano resonance is caused by the interference between additional LSPR at the middle structure and LSPR at the left CR.

Figure 2. (a) Transmission spectra of the proposed crossed metasurface, the red line shows the transmission spectra when there is only left CR with $r_{1in} = 75$ nm and $r_{1out} = 100$ nm, the black line shows the transmission spectra when there is only right CR with $r_{2in} = 65$ nm and $r_{2out} = 90$ nm, and the blue line shows the transmission spectra when there are right and left CRs arranged on the substrate with $r_{1in} = 75$ nm, $r_{1out} = 100$ nm, $r_{2in} = 65$ nm, $r_{2out} = 90$ nm and $d = 60$ nm. (b) The electric field distribution E_z at the wavelength of 994.2 nm in the case of only right CR. (c) The electric field distribution E_z at the wavelength of 1023 nm in the case of only left CR. (d) and (e) The electric field distribution E_z at the wavelength of 891.1 nm and 1004 nm in the case of double CRs.

Then we study the dual-Fano resonances as a function of the radius r_{2out} for the right CR with $\Delta r_2 = r_{2out} - r_{2in} = 25$ nm when the polarization of the incident light is the x direction as depicted in Fig. 3 (a). We can see that Fano resonance shows red shift as the radius r_{2out} increases from 80 nm to 120 nm. But there is a special case when $r_{2out} = 100$ nm, it is because that the symmetric ring-shaped structure when $r_{2out} = 100$ nm, so the dual-Fano resonances turn into single Fano resonance. Then we discuss the electric field distribution E_z at 827.4 nm for $r_{2out} = 80$ nm, 955 nm for $r_{2out} = 90$ nm, 1023 nm for $r_{2out} = 110$ nm, and 1045 nm for $r_{2out} = 120$ nm as shown in Fig. 3(b)-2(e). Figure 2(b) shows that the electric field are confined at the right side of the crossed nanostructure, and the same symbols of electric charges are distributed on the same CR, it is because that the r_{2out} for the right CR is so small. As the $r_{2out} = 90$ nm for the right CR, the electric field are confined at the left side of the crossed nanostructure. Especially, the inverse symbols of electric charges are distributed on the same CR when $r_{2out} = 110$ nm and 120 nm. Thus, we can see that the electric field distribution is completely opposite when the right CR is smaller or bigger than left one. But the dual-Fano resonances can always be observed in the asymmetric case for the proposed crossed metasurface.

Figure 3. (a) Transmission spectra of the proposed crossed metasurface as a function of the radius r_{2out} for the right CR with $\Delta r_2 = r_{2out} - r_{2in} = 25$ nm, $r_{1in} = 75$ nm, $r_{1out} = 100$ nm, and $d = 60$ nm. (b) The electric field distribution E_z at the wavelength of 827.4 nm when $r_{2out} = 80$ nm. (c) The electric field distribution E_z

at the wavelength of 955 nm when $r_{2out} = 90$ nm. (d) The electric field distribution E_z at the wavelength of 1023 nm when $r_{2out} = 110$ nm. (e) The electric field distribution E_z at the wavelength of 1045 nm when $r_{2out} = 120$ nm.

The distance d between the center of the two CRs in x direction is one of important factors for regulating dual-Fano resonances in our proposed crossed ring-shaped metasurface. Thus, we investigate the transmission spectra as a function of the distance d when $r_{1in} = 75$ nm, $r_{1out} = 100$ nm, $r_{2in} = 65$ nm, $r_{2out} = 90$ nm and the polarization of the incident light is the x direction. We can see that the transmission dip 1 and dip 2 show blue shift as d increases from 60 nm to 120 nm as shown Fig. 4(a). However, the transmission dip 3 shows red shift as d increases. The most interesting thing is that the transmission dip 2 gradually disappeared and the transmittance for the dip 1 increases with the increasing of the distance d . This is because the additional LSPR mode disappears as the distance d increases. Then we discuss the transmission spectra as a function of θ between the direction of polarization and the x -axis in the x - y plane when $r_{1in} = 75$ nm, $r_{1out} = 100$ nm, $r_{2in} = 65$ nm, $r_{2out} = 90$ nm, and $d = 60$ nm. We can see that the dual-Fano resonances turn into single Fano resonance when the θ increases from 30° to 90° , and the transmission spectra show blue shift with the increasing of θ as shown in Fig. 4(b). These results will provide guidance for the regulation of Fano resonance.

Figure 4. (a) Transmission spectra of the proposed crossed metasurface as a function of the distance d with $r_{1in} = 75$ nm, $r_{1out} = 100$ nm, $r_{2in} = 65$ nm, $r_{2out} = 90$ nm, $\theta = 0^\circ$. (b) Transmission spectra of the proposed crossed metasurface as a function of θ with $r_{1in} = 75$ nm, $r_{1out} = 100$ nm, $r_{2in} = 65$ nm, $r_{2out} = 90$ nm, $d = 60$ nm.

As is well-known, the sharp spectral lines for Fano resonance can effectively enhance the sensitivity of refractive sensing. Thus, we study sensing properties versus refractive index (RI) of external environment in the proposed crossed ring-shaped metasurface when $\theta = 0^\circ$, $r_{1in} = 75$ nm, $r_{1out} = 100$ nm, $r_{2in} = 65$ nm, $r_{2out} = 90$ nm and $d = 60$ nm. We can see that the dual-Fano resonances show red shift when RI increases from 1.00 to 1.04 as shown in Fig. 5(a). We can see that the resonant wavelength (FW) for Fano resonance peak 1 shows a linear increase with the increasing of RI as shown in Fig. 5(b). In order to investigate the sensing performance of the proposed crossed metasurface, we introduce the definition of the sensitivity as $s = \Delta\lambda / \Delta RI$, where λ is the FW for Fano resonance peak. Based on the definition of the sensitivity s , we can see that the maximum of the sensitivity $Max[s] = 1010$ nm/RIU for the Fano resonance peak 1 in the proposed crossed ring-shaped metasurface. The FW of Fano resonance peak 2 versus RI as depicted in Fig. 5(c). We can see that FW of Fano resonance peak 2 increases as RI increases. Then the maximum of sensitivity at Fano resonance peak 2 $Max[s] = 1300$ nm/RIU can be observed. The result will have great significance to design ultra-high sensitive nanosensors.

Figure 5. (a) Transmission spectrum of the proposed crossed metasurface as a function of RI with $r_{1in} = 75$ nm, $r_{1out} = 100$ nm, $r_{2in} = 65$ nm, $r_{2out} = 90$ nm, $d = 60$ nm, $\theta = 0^\circ$. (b) The FW of Fano resonance peak 1 versus RI (c) The FW of Fano resonance peak 2 versus RI.

4. Conclusions

In summary, we have studied dual-Fano resonances and high-sensitivity sensing performance in the proposed crossed ring-shaped metasurface by use of FDTD simulation method. We can find that the dual-Fano resonances in the proposed crossed ring-shaped metasurface is caused by the destructive interference among three LSPRs (LSPR at the surface of left CR, right CR, and the crossed part at the middle of the left and right CRs). In addition, we can also see that the spectra of dual-Fano resonances can be effectively tuned by the radius of the CR, the distance between the center of the two CRs in x direction, and the polarization of the incident light. Especially, We can see that the dual-Fano resonances turn into single Fano resonance when the $\theta = 90^\circ$ or the distance $d = 120$ nm or $r_{2out} = 100$ nm. What is more, the maximum of sensitivities can reach up to 1010 nm/RIU and 1300 nm/RIU at Fano resonance peak 1 and Fano resonance peak 2 in our proposed crossed ring-shaped metasurface. The research results may play an important role for designing high sensitive nanosensors.

Declarations

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Figures

Figure 1

(a) Schematic diagram of the crossed ring-shaped metasurface, (b) x-y plane view of the proposed crossed ring-shaped metasurface.

Figure 2

(a) Transmission spectra of the proposed crossed metasurface, the red line shows the transmission spectra when there is only left CR with $r_{1in}=75$ nm and $r_{1out}=100$ nm, the black line shows the transmission spectra when there is only right CR with $r_{2in}=65$ nm and $r_{2out}=90$ nm, and the blue line shows the transmission spectra when there are right and left CRs arranged on the substrate with $r_{1in}=75$ nm, $r_{1out}=100$ nm, $r_{2in}=65$ nm, $r_{2out}=90$ nm and $d=60$ nm. (b) The electric field distribution E_z at the wavelength of 994.2 nm in the case of only right CR. (c) The electric field distribution E_z at the wavelength of 1023 nm in the case of only left CR. (d) and (e) The electric field distribution E_z at the wavelength of 891.1 nm and 1004 nm in the case of double CRs.

Figure 3

(a) Transmission spectra of the proposed crossed metasurface as a function of the radius r_{2out} for the right CR with $\Delta r_2=r_{2out}-r_{2in}=25$ nm, $r_{1in}=75$ nm, $r_{1out}=100$ nm, and $d=60$ nm. (b) The electric field distribution E_z at the wavelength of 827.4 nm when $r_{2out}=80$ nm. (c) The electric field distribution E_z at the wavelength of 955 nm when $r_{2out}=90$ nm. (d) The electric field distribution E_z at the wavelength of 1023 nm when $r_{2out}=110$ nm. (e) The electric field distribution E_z at the wavelength of 1045 nm when $r_{2out}=120$ nm.

Figure 4

(a) Transmission spectra of the proposed crossed metasurface as a function of the distance d with $r_{1in}=75$ nm, $r_{1out}=100$ nm, $r_{2in}=65$ nm, $r_{2out}=90$ nm, $\theta=0^\circ$. (b) Transmission spectra of the proposed crossed metasurface as a function of θ with $r_{1in}=75$ nm, $r_{1out}=100$ nm, $r_{2in}=65$ nm, $r_{2out}=90$ nm, $d=60$ nm.

Figure 5

(a) Transmission spectrum of the proposed crossed metasurface as a function of RI with $r_{1in}=75$ nm, $r_{1out}=100$ nm, $r_{2in}=65$ nm, $r_{2out}=90$ nm, $d=60$ nm, $\theta=0^\circ$. (b) The FWHM of Fano resonance peak 1 versus RI. (c) The FWHM of Fano resonance peak 2 versus RI.