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A liquid crystals modulated optical tunable filter based on Fano resonance of Au nanorod trimer

Huan Peng Xin[a], Fei Liu[a,*], Guang Jun Ren[a,*], Hong Liang Zhao[a], Jian Quan Yao[b]

[a] School of Electronics Information Engineering, Tianjin Key Lab. of Film Electronic & Communication Devices, Engineering Research Center of Communication Devices and Technology, Ministry of Education, Tianjin University of Technology, Tianjin 300384, PR China

[b] College of Precision Instrument and Opto-electronics Engineering, Institute of Laser and Opto-electronics, Key Laboratory of Opto-electric Information Science and Technology, Ministry of Education, Tianjin University, Tianjin 300072, PR China

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ABSTRACT

We theoretically studied the liquid crystals modulated optical tunable filter based on Fano resonance of Au nanorod trimer. Plasmonic nanorods can support Fano resonances, where the line shape characteristics are controlled by the geometry of nanorods. Here a polarization-dependent Au nanorod trimer was designed, where the three nanorods have the same geometric parameters and form a C-shape. When the plasmon modes of the longitudinal nanorod and the two transverse nanorods couple at resonance wavelength, a Fano resonance occurs. Due to liquid crystals can change the polarization direction of light, the transmission spectra of Au nanorod trimer can be switched on and off with different phases of liquid crystals when incident light passes through liquid crystals before reaching the Au nanorod trimer. Furthermore, filter optical characteristics are highly tunable by changing the thicknesses of Au nanorod trimer and its coating layer. Fano resonances show a large light extinction in periodic array of assembled nanorods, which can be used in optical tunable filter and optical switch.

1. Introduction

Localized surface plasmon resonances (LSPRs) [1–4], defined as the collective oscillations of the electrons of metallic nanostructures, have attracted significant attentions in the past decades due to the interesting physics and important applications such as surface-enhanced Raman scattering [5], chemical and biomolecular sensing [6–9], subwavelength optical waveguiding [10,11], and nonlinear optics [12,13]. Nanoparticles can exhibit unique, hybridized plasmon modes when they couple to adjacent nanoparticles [14]. These hybridized modes can in turn interact by various physical mechanisms, resulting in asymmetrical lineshapes and interference phenomena such as Fano resonances [15,16]. A Fano resonance can arise from the destructive interaction of a broad, superradiant mode and a narrow, subradiant mode [17–19]. The superradiant, “bright” plasmon mode can be excited directly by incident light , on the contrary the subradiant, “dark” plasmon mode cannot efficiently couple with incident light [20]. Furthermore, the dark plasmon mode can be excited by the bright plasmon mode in the near field. Using numerical electromagnetic simulations, Prof. X. Zhang and co-workers have shown a strongly coupled system in dolmen-type structure for the first time [21]. The Fano resonance in this system is due to the coupling of “the radiative antenna” excited by the incident plane wave with “the dark atom”. From the transmission spectra of nanostructure, we can find a Fano resonances caused narrow transparency window corresponding to the energy of the subradiant plasmon mode.

As Fano resonances arise from the interparticle coupling, they are sensitive to the changes in geometry and local environment: small perturbations can induce dramatic resonance or lineshape shifts. This unique property of Fano resonances can be used in many applications such as sensor, optical filter and optical switch [22]. However, these Fano resonance-based applications critically depend on the ability to control or modulate the Fano resonance by external means. Liquid crystals (LCs) are promising candidate for the modulation of Fano resonances due to their large birefringence, low driving threshold, and versatile driving methods [23–28]. Optical anisotropy plays an essential role in changing the polarization state of light in LCs. For the polarization-dependent nanostructure, the transmission spectra will display different lineshapes with different phases of LCs when incident light passes through LCs before reaching the nanostructure [29,30]. Therefore, the Fano resonance can be modulated by LCs with different phases (homogeneous nematic phase and twisted nematic phase).

In this paper, we demonstrate the modulation of the Fano resonance of a plasmonic Au nanorod trimer in LCs controlled optical

* Corresponding authors.
E-mail addresses: xinhuanpeng123@163.com (H.P. Xin), feiliu@tju.edu.cn (F. Liu), rgj1@163.com (G.J. Ren).

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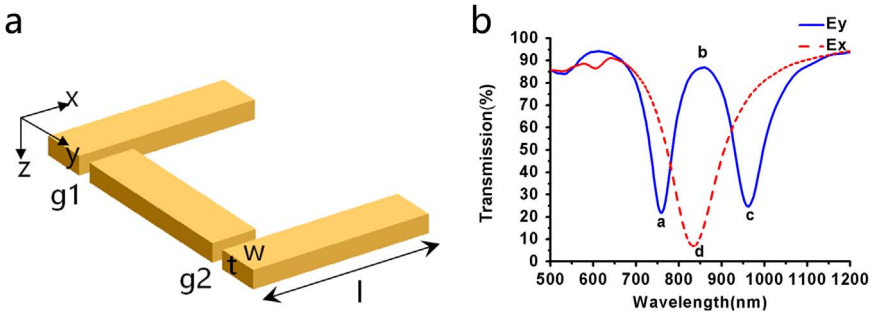

Fig. 1. (a) Schematic diagram of the Au nanorod trimer. (b) Simulated transmission spectra of the Au nanorod trimer with polarization Ey and Ex.

tunable filter. An asymmetric Au nanorod trimer was designed, where the three nanorods have the same geometric parameters and form a C-shape. Its constitution and geometric parameters are different from the dolmen-type structure proposed by Prof. X. Zhang. It is the same geometric parameters that provide us with a controllable transparency window. The Au nanorod trimer has strong polarization-dependent transmission spectra, possessing a strong Fano resonance for one polarization orientation and no Fano resonance for the orthogonal polarization. We modulated the polarization of incident light by using LCs. The phase of the LCs can be controlled by the applied voltage (Here, we do not discuss the relationship between applied voltage and LCs). By integrating this Au nanorod trimer into LCs modulated optical tunable filter, we can switch on and off the transmission spectra by setting different phases of LCs.

2. Nanostructure and simulation method

Firstly, the structure of Au nanorod trimer is introduced. Fig. 1(a) schematically shows the Au nanorod trimer. All the nanorods used have the same geometric parameters: length l=120 nm, width w=30 nm and thickness t=20 nm in the z-direction. The gaps between the nanorods are g1=g2=10 nm. Gold is chosen as the material and its refractive index is taken from Ref. 31. In order to avoid the plasmon modes coupling between the adjacent trimers, we set the periods of the Au nanorod trimer (from edge to edge) with p_x=220 nm along the x-direction and p_y=300 nm along the y-direction. A plane light wave is incident along the z-direction, with a polarization direction of the electric field along x-direction (Ex) or y-direction (Ey).

We simulated the Au nanorod trimer and the tunable filter by using the finite difference time domain (FDTD) method [32], in which Maxwell's equations are solved numerically on discrete grids involving space and time. The refractive index of the background is 1.

3. Results and discussion

Fig. 1(b) schematically shows the simulated transmission spectra of the Au nanorod trimer surrounded by air (refractive index is 1). The blue curve and the red curve represent the transmission spectra of the Au nanorod trimer with the polarization Ey and Ex respectively. With the Ey polarization the asymmetric Au nanorod trimer displays a strong Fano resonance with the characteristic transparency window at point b, while with the Ex polarization no Fano resonance is observed. Due to all the nanorods have the same geometric parameters, we can find that the transmission peak (point b) and the transmission dip (point d) are at similar wavelengths. This provides us with a transparency window, which can be switched on and off with different polarization directions of incident light.

In order to understand the origin of the Fano resonance, Fig. 2 shows the electric field and charge distributions of the Au nanorod trimer at point a (Fig. 2(a)), b (Fig. 2(b)), c (Fig. 2(c)) and d (Fig. 2(d)).

From Fig. 2(a) and (c), we can find that the electric field intensity is larger at the corners of the longitudinal nanorod. The charge distributions show that the longitudinal nanorod is a dipole exhibiting a superradiant bright plasmon mode. This bright mode is excited by the incident light directly. When the longitudinal nanorod couples to the two transverse nanorods, dipole modes with out-phase charge distributions can both exhibit in the two transverse nanorods. As shown in Fig. 2(a), the wavelength is shorter than the resonance wavelength b, the charge distributions of adjacent nanorods are anti-bonding modes. On the contrary, the wavelength c is longer than the resonance wavelength, the charge distributions of adjacent nanorods are bonding modes shown in Fig. 2(c). When the longitudinal nanorod couples to the adjacent nanorods at the wavelength b, the Fano resonance occurs. In Fig. 2(b), the electric field around the longitudinal nanorod is very weak because of the destructive interference between the two excitation paths: one path is that the longitudinal nanorod is excited directly by the incident light, and the other is indirectly by the coupling of the longitudinal nanorod with the two transverse nanorods [33]. The two pathways have the phase difference of π and lead to a destructive interference. From Fig. 2(d), we find that the two transverse nanorods have a strong electric field and show the same bright dipole modes with in-phase charge distributions, while the longitudinal nanorod has a weak electric field and shows a dark mode.

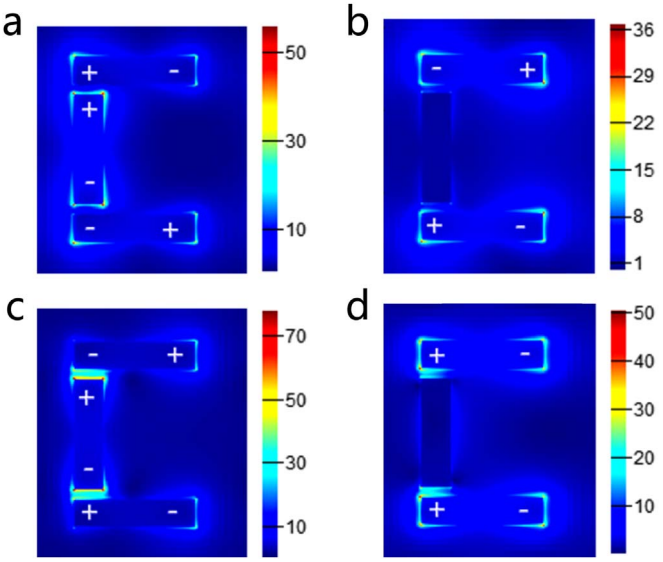

Fig. 2. Simulated electric field and charge distributions of the Au nanorod trimer at different wavelengths in the x-y plane. (a) Transmission dip at point a. (b) Transmission peak at point b. (c) Transmission dip at point c. (d) Transmission dip at point d.

We all know that the intensity of inter-rod coupling depends on the spacing of two rods as the inter-rod coupling becomes weaker once the spacing gets larger. Fig. 3 shows the simulated transmission spectra of the Au nanorod trimer with different spacing (gap g) with the Ey polarization. We can find that with the increase of spacing, the second transmission dip is becoming smaller and smaller, and it is changing more quickly in Fig. 3(a) than in Fig. 3(b). Due to the first transmission