Sensors and Actuators A 234 (2015) 346–350

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Double Fano resonances in a planar pseudo-dolmen structure

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ARTICLE INFO

Article history:
Received 7 August 2015
Received in revised form
15 September 2015
Accepted 19 September 2015
Available online 25 September 2015

Keywords:
Fano resonance
Localized surface plasmon
Plasmonics

ABSTRACT

The transmittance properties of a planar pseudo-dolmen plasmonic structure were investigated using finite element method. Numerical results show that double Fano resonances are caused by the strong electric field coupling between bright and dark modes. The dark plasmon resonances are highly dependent on the structure parameters of the pseudo-dolmen structure. The Fano resonances in the pseudo-dolmen structure are also sensitive to small changes in the refractive index of the surrounding media. This characteristic could be effectively used to fabricate bi-wavelength sensors.

1. Introduction

In 1961, Ugo Fano described the asymmetric spectral lineshape with the expression of the form $I \propto (F\gamma + \omega - \omega_0)^2 / \left[(\omega - \omega_0)^2 + \gamma^2\right]$, where ω_0 and γ are standard parameters that denote the position and width of the resonance, respectively; F is the so-called Fano parameter, which describe the degree of asymmetry [1]. Recently, Fano resonances in a plasmonic system have been extensively studied because of their potential applications in chemical and biological sensors [2–4], slow light [5,6], surface enhanced Raman scattering [7,8], and plasmon rulers [9].

Fano resonance is caused by hybridization between a narrow discrete resonance (dark mode) and a broad continuum state (bright mode) [10]. A bight mode is excited by incident light, and a dark mode is indirectly excited through coupling with the bright mode [11]. Tuning Fano resonances is important to modify optical responses by changing the asymmetric line shape and the localized electromagnetic field distribution in the dark mode. Many researchers have focused on Fano resonances in various plasmonic systems, such as dolmen nanostructures [6,12,13], nanoparticle clusters [14–16], metal-nanoshells [17], metal dimers [18,19], and ring/disk cavities [20].

Many efforts were spent to make 2D plasmonic material, such as the highly doped 2D MoS_2 and molybdenum oxide nanoflakes, with resonant wavelengths in near IR and visible regions [21,22]. Despite considerable efforts to achieve single Fano resonance in different types of plasmonic structures, several designs have achieved multiple Fano resonances; these designs include metal-dielectric core–shell nanoparticle oligomers (MDCSs) [23], dimer/monomer slab and ring-near-disk cavity (RNDC) [24], asymmetrically split rings (ASR) [25], and double symmetrical U-shaped split-ring resonators (SRRs) with a nanorod between the two SRRs (SRRs/Rod) [26]. Dark modes are generated in plasmonic systems with different designs to obtain multiple Fano resonances. In the MDCS structure, an additional dark mode is provided by adding dielectric to the heptamer structure [23]. In dimer/monomer slab and RNDC structures, multiple Fano resonances arise for the same structures with larger dimensions [24]. In the ASR structure, double dark modes are generated by introducing structural symmetry breaking [25]. In the SRR/Rod structure, an additional dark mode is provided by changing the coupling distance between the nanorod and the double symmetrical U-shaped split-ring resonators [26]. In general, the double Fano resonances are realized in a relatively complex structure for inducing one more dark mode.

In this paper, we demonstrate that the occurrence of two Fano resonances in a planar pseudo-dolmen structure (PDS) is caused by the electric field coupling between nanorods with different lengths. Numerical calculations show that the Fano resonances are strongly dependent on the length of nanorods in the PDS structure and on the separation between adjacent nanorods. Two dark modes can be tuned independently by varying the length of nanorods as well as the separation between them. And they are sensitive to the refractive index changes of the surrounding environment. This characteristic could be effectively used to fabricate double-wavelength sensors.

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http://dx.doi.org/10.1016/j.sna.2015.09.029

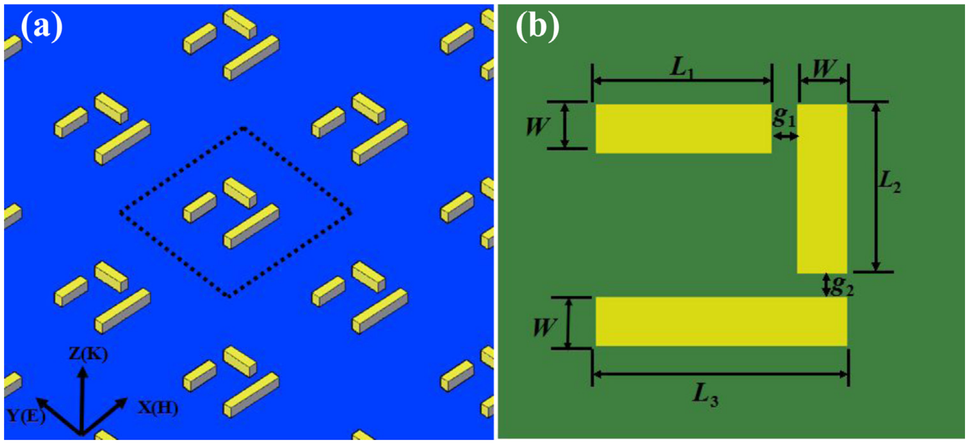

Fig. 1. (a) Pseudo-dolmen structure arrays and (b) the unit cell with geometrical parameters.

2. Structure and computational method

Fig. 1 presents the periodic PDS arrays and their structural parameters. The PDS consists of three metallic nanorods arranged perpendicularly to each other. The incident light normally illuminates the structure along the –*z* direction with polarization along the *y* direction. The lengths of nanorods 1–3 are defined as L_1, L_2, and L_3, respectively. Fig. 1 shows that the gap between the nanorods is $g_1 = g_2 = 10$ nm, and the period in the *x* and *y* directions is 200 nm. The three metallic nanorods also demonstrate a fixed square cross section of 20 nm × 20 nm.

The transmittance spectra of the PDS arrays are derived using the three-dimensional finite element method with the software COMSOL Multiphysics simulation. The stationary frequency solver is applied for this static situation. Periodic boundary conditions are imposed on four sides of the unit cell to simulate the infinite 2D array. The refractive index of the surrounding media is 1, and the selected metallic element is gold, whose frequency-dependent permittivities are obtained from Ref. [27].

3. Results and discussion

Fig. 2(a) shows the transmittance spectrum of the PDS with $L_1 = L_2 = 70$ nm, $L_3 = 100$ nm, and $g_1 = g_2 = 10$ nm. Three resonant wavelengths appear in the spectra at $\lambda = 642$ nm, 702 nm, and 824 nm. For comparison, the longitudinal modes of these nanorods with similar parameters to those in Fig. 2(a) are calculated. Fig. 2(b) and (c) indicate that the longitudinal resonant modes for nanorods 1 (or 2) and 3 are $\lambda = 660$ nm and 770 nm, respectively.

The electric field spatial distribution in the resonant modes in Fig. 2(a) is calculated to elucidate the resonance characterizes of the PDS. Fig. 3(a) indicates that the electric fields are mainly distributed at the two ends of nanorod 2 at $\lambda = 642$ nm. This mode is mainly due to the dipole electric oscillation on nanorod 2. This mode can be excited under the *y* direction polarization incidence and is called the bright mode (mode B, resonant wavelength λ_B). Fig. 3(b) shows that strong electric fields appear at the two ends of nanorods 1 and 2 at $\lambda = 702$ nm. Specifically, strong electric fields exist between nanorods 1 and 2. The incident light with *y* direction polarization excites electron oscillations in the *x* direction on nanorod 1. This mode is a dark mode and denoted as mode D_1 with the resonant wavelength λ_{D_1}. Fig. 3(c) demonstrates that the strong electric fields appear at the two ends of nanorods 2 and 3 at $\lambda = 824$ nm. In particular, strong electric fields exist between nanorods 2 and 3. The incident light with *y* direction polarization excites electron oscillation in the *x* direction on nanorod 3. This mode is a dark mode and denoted as mode D_2 with the resonant wavelength λ_{D_2}. From these results, one bright mode (mode B) and two dark modes (modes D_1 and D_2) can be excited for the PDS. The well-separated dark modes in the transmission spectrum confirm that the PDS is a simple structure that can achieve double Fano resonances.

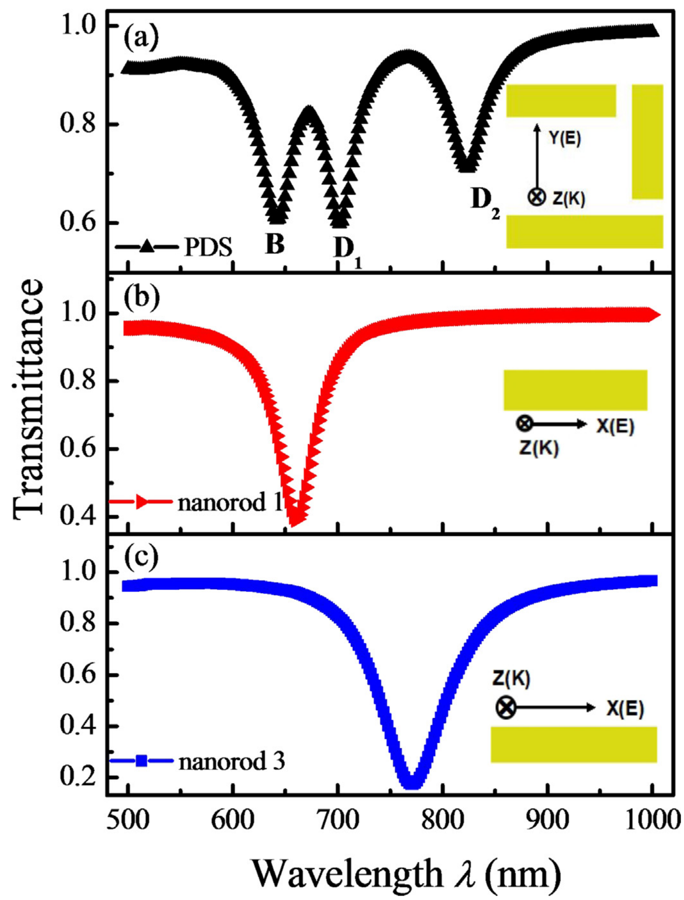

Fig. 2. Transmittance spectra of (a) PDS with E_y polarization, (b) nanorod 1 with longitudinal polarization, and (c) nanorod 3 with longitudinal polarization.

The dimensions of the PDS are systematically varied to investigate the effects of structural parameters on the Fano resonances. First, L_1 is varied to study the effect of the length of nanorod 1 on the Fano resonances of the PDS as shown in Fig. 4(a). The gap between adjacent nanorods is set at 10 nm. Fig. 4(a) shows that modes B and D_1 red shift with the extension of L_1, and mode D_2