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Double Fano resonances in a planar pseudo-dolmen structure

Na Li, XiaoJun Tian, Wan Zhang, Lina Luo, Guian Li, Zhongyue Zhang*

School of Physics and Information Technology, Shaanxi Normal University, Xi'an 710062, China

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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.

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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.

* Corresponding author. Tel.: +86-029-81530764.
E-mail address: zyzhang@snnu.edu.cn (Z. Zhang).

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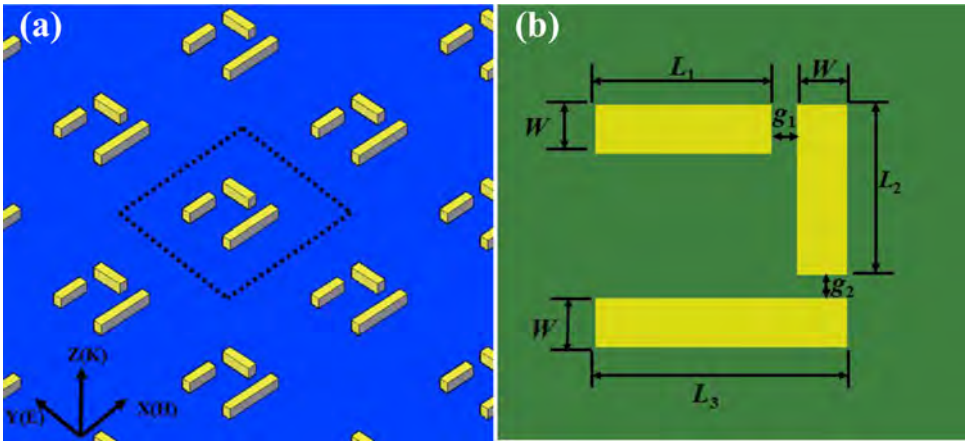

Fig. 1. (a) Pseudo-dolmen structure arrays and (b) the unit cell with geometrical parameters.

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

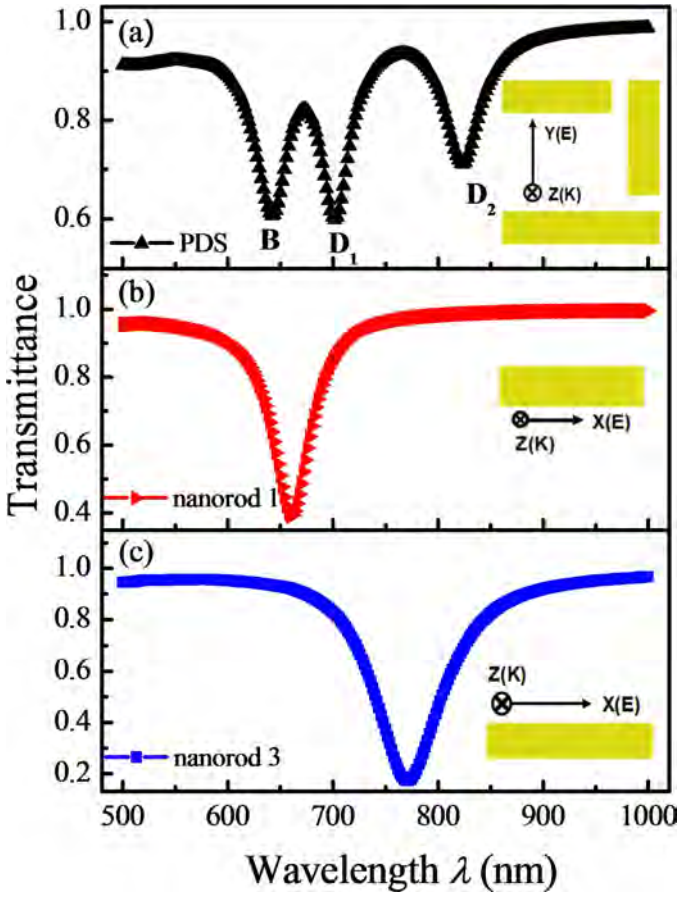

Fig. 2. Transmittance spectra of (a) PDS with E_y polarization, (b) nanorod 1 with longitudinal polarization, and (c) nanorod 3 with longitudinal polarization.

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.

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

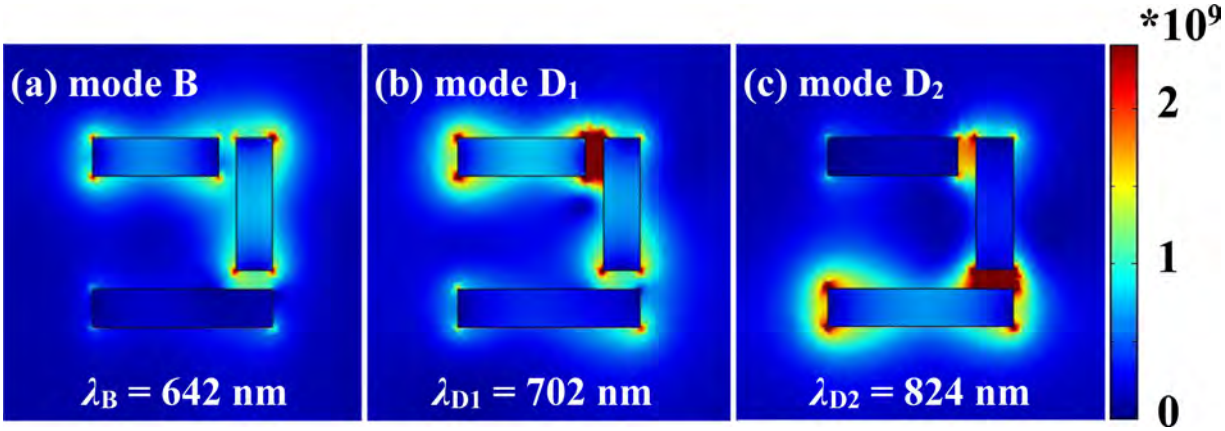

Fig. 3. Electric field distributions of the PDS at different modes (a) mode B, (b) mode D_1, and (c) mode D_2.

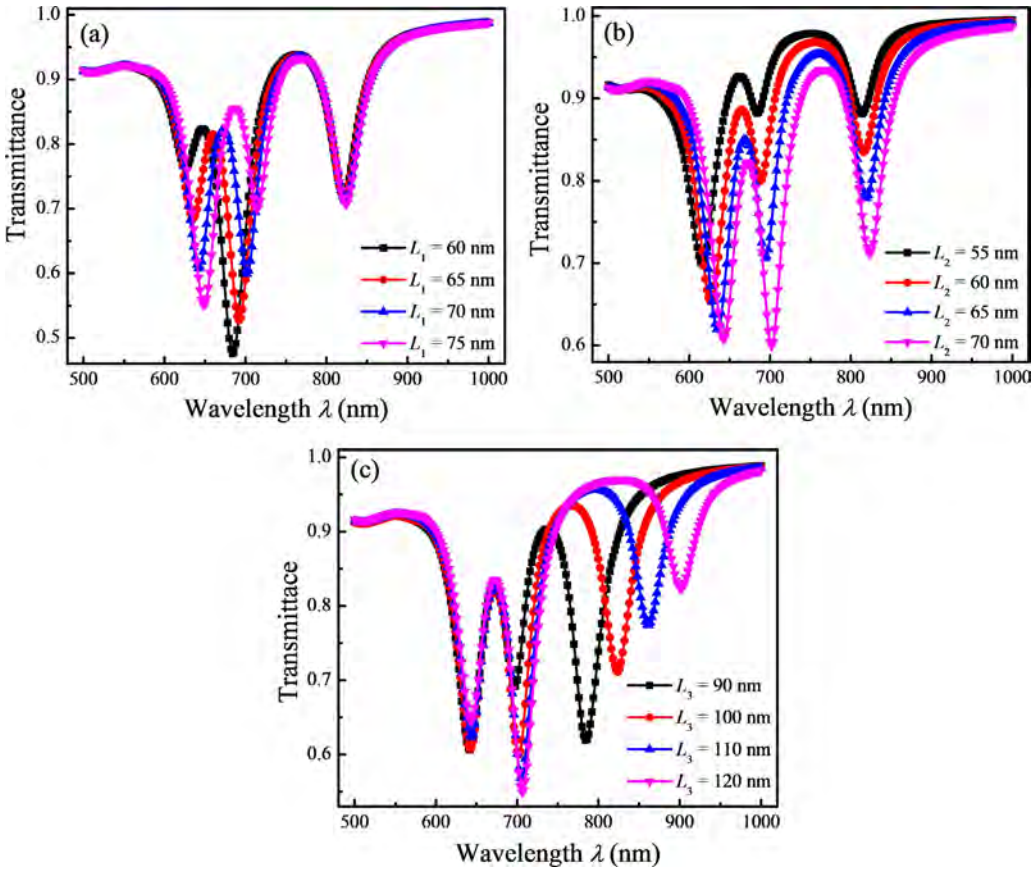

Fig. 4. Transmittance spectra of the PDS with different nanorod lengths: (a) different L_1; (b) different L_2; (c) different L_3.

does not evidently shift. Fig. 3(a) presents a weak electric field coupling between nanorods 1 and 2 of mode B. The increasing length of nanorod 1 extends the electron oscillations of mode B, causing the mode to red shift. The increment in L_1 also extends the electron oscillations of mode D_1 and results in the red shift of the mode. By contrast, the increment in L_1 does not affect mode D_2 because the mode is mainly caused by the electron oscillations on nanorods 2 and 3. As a result, mode D_1 can be tuned independently by varying the length of L_1. Fig. 4(b) further shows the transmittance spectra of the PDS with different L_2 values and a fixed gap of 10 nm. All resonant modes red shift with increasing L_2 values because of the increasing electron oscillation length in the resonant modes. Fig. 4(c) indicates that mode D_2 red shifts with the extension of L_3, and mode B and D_1 do not evidently shift. The increment of L_3 only increases the electron oscillation length of mode D_2. Thus, mode D_2 can also be tuned independently by varying the length of L_3.

The gaps g_1 and g_2 are varied with fixed $L_1 = L_2 = 70$ nm and $L_3 = 100$ nm to investigate their effects on Fano resonances of the PDS. Fig. 5(a) shows the transmittance spectra of the PDS with $g_1 = 10$ nm, 15 nm, 20 nm, and 25 nm and $g_2 = 10$ nm. The increase in g1 weakens the coupling between nanorods 1 and 2; The weakened coupling decreases the electron oscillation length of mode D_1 and leads to the evident blue shift of λ_{D_1} Fig. 5(b) presents the transmittance spectra of the PDS with $g_2 = 10$ nm, 15 nm, 20 nm, and 25 nm and fixed $g_1 = 10$ nm. With increasing g_2, mode D_2 blue

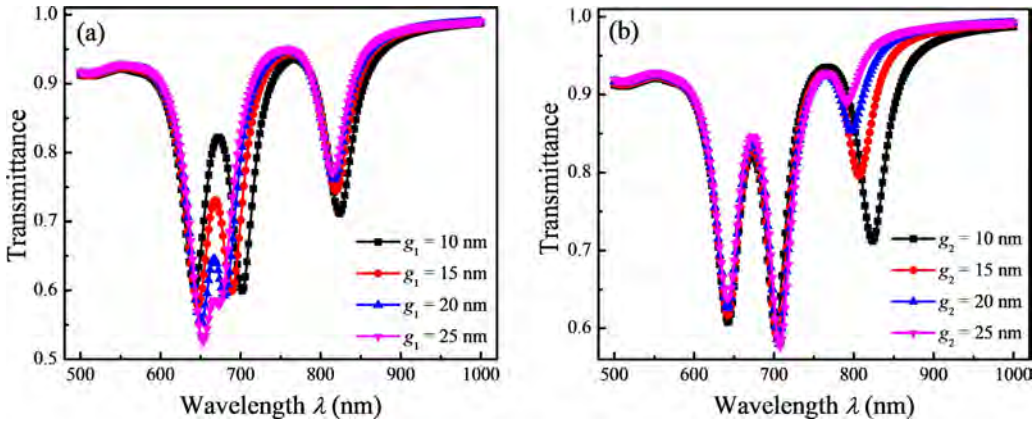

Fig. 5. Transmittance spectra of the PDS with different gaps: (a) different g_1; (b) different g_2.

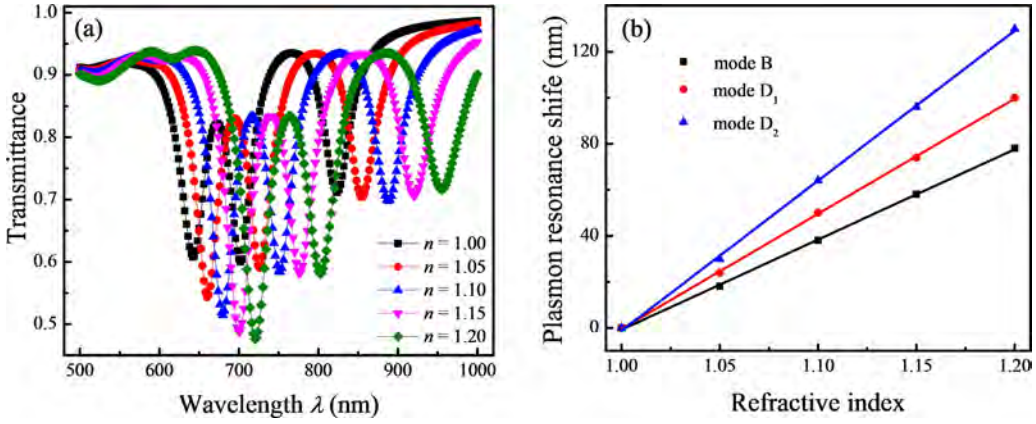

Fig. 6. (a) Transmittance spectra of PDS with the environments of different refractive indexes; (b) the resonance wavelengths as a function of refractive index.

shifts because of the decreasing coupling strength. But modes B and D_1 are not affected.

The value of n is increased from 1 to 1.2 with fixed $L_1 = L_2 = 70$ nm, $L_3 = 100$ nm, and $g_1 = g_2 = 10$ nm to investigate how the dielectric constants of the surrounding media affect the sensing performance. Fig. 6(a) shows that all resonance modes red shift with increasing refractive index of the dielectric environment. Fig. 6(b) also presents that the plasmon resonance shifts with increasing of the refractive index of the surrounding media. The lines in Fig. 6(b) represent the linear fittings. The resonant wavelengths of the three modes show a linear relationship to n. The calculated sensitivities are $S_B = 378$ nm/RIU, $S_{D_1} = 492$ nm/RIU, and $S_{D_2} = 630$ nm/RIU.

A high figure of merit (FOM) is preferred than the index shift of plasmon resonance for sensing applications because of its narrow width. FOM is used to directly compare the overall performance of sensors by using the following formula $FOM = m/fwhm$, where $fwhm$ is the full width at half the maximum centered at the resonance wavelength λ, and m is the linear regression slope for the refractive index dependence (i.e., spectral shifts per refractive index) [28]. The $fwhm$ values of modes B, D_1, and D_2 are $fwhm_B = 0.0743$ eV (30 nm), $fwhm_{D_1} = 0.0561$ eV (28 nm), and $fwhm_{D_2} = 0.0499$ eV (34 nm), respectively; their corresponding m values are mB = 1.053 eV/RIU, $m_{D_1} = 1.103$ eV/RIU, and $m_{D_2} = 1.03$ eV/RIU, respectively. The calculated FOMs of modes B, D_1, and D_2 are $FOM_B = 14.73$, $FOM_{D_1} = 20.44$, and $FOM_{D_2} = 21.22$, respectively. These FOMs are stronger than those of the individual plasmonic particles [24]. The high FOM based on plasmonic mode coupling may be useful for applications requiring high-sensitivity detection.

4. Conclusions

In this study, a planar PDS is proposed to create two dark modes and then to generate double Fano resonances. Dark mode D_1 is introduced by the coupling effect between nanorods 1 and 2, and dark mode D_2 is introduced by the coupling between nanorods 2 and 3. The dark modes are highly dependent on the structural parameters of the PDS and can be tuned independently. The influences of the refractive index on the bright and dark modes are investigated for sensing applications. The results show the potential applications of the PDS in single- or double-wavelength sensing.

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Biographies

Na Li was born in China in 1995. She is an junior student of School of Physics and Information Technology, Shaanxi Normal University, Xi'an, China. Her interests are micro-nano optics and photonics.

Xiaojun Tian was born in China in 1993. She is a senior student of School of Physics and Information Technology, Shaanxi Normal University, Xi'an, China. Her interests are micro-nano optics and photonics.

Wan Zhang was born in 1990. She is an graduate student of school of Physics and Information Technology, Shaanxi Normal University, Xi'an, China. Her interests are micro-nano optics and photonics.

Lina Luo was born in China in 1989. She is an master graduate student of Physics and Information Technology, Shaanxi Normal University, Xi'an, China. Her interests are micro-nano optics and photonics.

Guian Li was born in China in 1966. He got his Ph.D from School of Electronic and Information Engineering of Xian Jiao Tong University, China. His interests is optoelectronic information materials. At present, he is working as a chief of the education administration division at Shaanxi Normal University, China.

Zhongyue Zhang was born in China in 1975. He received his Ph.D from University of Georgia, and he is working as a vice-president at School of Physics and Information Technology, Shaanxi Normal University. His research interests deals with micro-nano optics and photonics.