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The bright–bright and bright–dark mode coupling-based planar metamaterial for plasmonic EIT-like effect

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ABSTRACT

In this paper, we propose a novel planar metamaterial structure for the electromagnetically induced transparency (EIT)-like effect, which consists of a split-ring resonator (SRR) and a pair of metal strips. The simulated results indicate that a single transparency window can be realized in the symmetry situation, which originates from the bright–bright mode coupling. Further, a dual-band EIT-like effect can be achieved in the asymmetry situation, which is due to the bright–bright mode coupling and bright–dark mode coupling, respectively. Different EIT-like effect can be simultaneously achieved in the proposed structure with the different situations. It is of certain significance for the study of EIT-like effect.

1. Introduction

Metamaterial is a new type of artificially-fabricated material, which has attracted considerable attentions and investigations due to its special electromagnetic responses [1]. As one of the most significant properties, the characteristic of the well-controlled of incident electromagnetic waves has been extensively applied in the fields of negative refractive index materials [2,3], extraordinary optical transmission [4–7], perfect absorption [8] and so on. As a result of a quantum destructive interference phenomenon between two excited pathways in three-level atomic system, the EIT effect can lead to an extremely narrowband transparency window over a broad absorption spectrum [9], and has the potential applications in optical sensors [10,11], nonlinear optical processes [12,13] and low-loss slow-light devices [14,15]. However, the strictly experimental conditions in the atomic system such as the coherent high intensity pumping and the cryogenic temperature have immensely restricted its performance and further investigations. In order to break the constraint, recently, many attentions have been paid to the analogy of EIT effect in plasmonic metamaterials, which can extended the limitation and realize EIT-like effect in normal environment.

In general, the bright–dark and bright–bright mode coupling are always regarded as the efficiently excited way to realize EIT-like behavior in metamaterials [15,16]. The bright mode usually denotes the superradiant property (high radiative losses) and can be coupled with propagating waves directly, while the dark mode possesses a high quality factor due to the subradiant property and cannot be excited directly except for the near-field coupling [17,18]. After the existence of EIT-like effect in metamaterials has been confirmed [18–25], many metamaterials have been reported to realize the EIT-like effect at the wavelength of microwave [26–28], terahertz (THz) [17,29], near-infrared [30–32] and optical regions [16,33–35] based on two different mode couplings. However, most of the previous studies were based on the bright–dark mode coupling and the asymmetry of unit cell structure.

In this paper, a novel planar metamaterial structure was designed to gain the EIT-like effect at optical region both in the symmetry and asymmetry structure. In the symmetry condition, a single sharp transmission peak could be achieved in a dip background owing to the coupling of bright–bright mode, which was different from most previous studies based on bright–dark mode coupling in an asymmetry structure. Further, two adjacent EIT peaks could be gained when the symmetry of the unit cell was broken. In addition, it could be confirmed that the two EIT transparency windows results from the bright–bright and bright–dark mode coupling, respectively. In other words, the two different modes coupling could coexist in the proposed system, which have rarely reported in previous studies. Our work not only provides an

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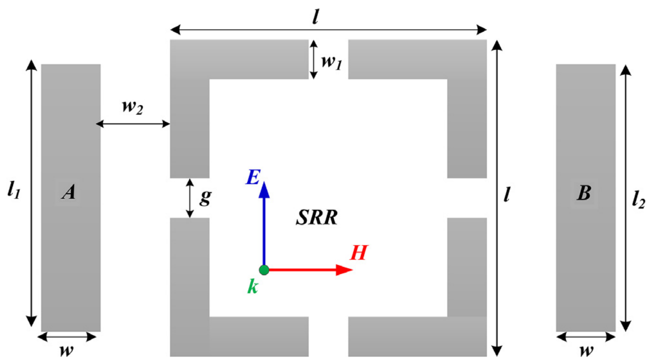

Fig. 1. The schematic illustration of the plasmonic metamaterial structure and the incident field polarization with the geometrical parameters of $l = 320$ nm, $w_1 = 40$ nm, $g = 40$ nm, $l_1 = l_2 = 270$ nm, $w = 60$ nm, $w_2 = 70$ nm.

efficient way to obtain multiple EIT-like effects but also opens up a new perspective for the study of the plasmonic EIT effect.

2. Structure description and numerical model

Fig. 1 shows a unit cell schematic illustration of the proposed system based on the planar plasmonic metamaterial, which consists of a split-ring resonator and a pair of strips (*A* and *B*). The two strips are symmetrically placed on both sides of the SRR, which makes the compound structure to show a highly symmetry. The geometrical parameters of the square SRR are $l = 320$ nm, $w_1 = 40$ nm, and $g = 40$ nm. The geometrical parameters of the two identical metal strips are $l_1 = l_2 = 270$ nm and $w = 60$ nm. The distances between the SRR and the two strips are $w_2 = 70$ nm. The thickness of each planar element is $t = 40$ nm. The periodicity in x and y directions is $P_x = P_y = 700$ nm in free space and only a single layer is considered in the transmission direction. Plane wave is selected as the illuminant and vertical to the planar of the unit cell with the electric field E along the $y$direction, as shown in Fig. 1. The transmission response of the proposed system is investigated numerically with the finite difference time domain (FDTD) methods. Meanwhile the periodic boundary conditions (PBC) and the perfectly match layers (PML) boundary conditions in the transmission direction of incidence are utilized. During the simulating, the hexahedral grids with mesh size of 3 nm in the time domain solver dialog and the adaptive local mesh refinement are applied to create an improved mesh, so that the simulated results can sufficiently converge. Silver is selected as the metal in the numerical model whose permittivity is described by the Drude model, with the plasmon frequency $\omega_p = 1.366 \times 10^{16}$ rad/s and a collision frequency $v_c = 3.07 \times 10^{13}$ Hz, respectively [18].

3. Results and discussion

In order to achieve the EIT-like effect, the resonant wavelengths of the two strips and the SRR are designed by adjusting their geometric parameters. The simulated electromagnetic responses of the two different configurations are shown in Fig. 2(a) and (b), in which we can find that both the two strips and the SRR are excited strongly by incident light and inspire a strong plasmon resonance at 885 nm and 933 nm, respectively. Therefore, these two elements show a strong absorption of incident light, which can be considered as a two-level atomic system [18]. It is clear see that the notch caused by the plasmon resonance in the double strips system has a lower Q factor ($\omega/\Delta\omega$), which is regarded as a radiative plasmonic state. On the contrary, the SRR system is a subradiant (dark mode) state, which weakly couples with the incident field. Further, when the two substructures are combined into a compound structure as

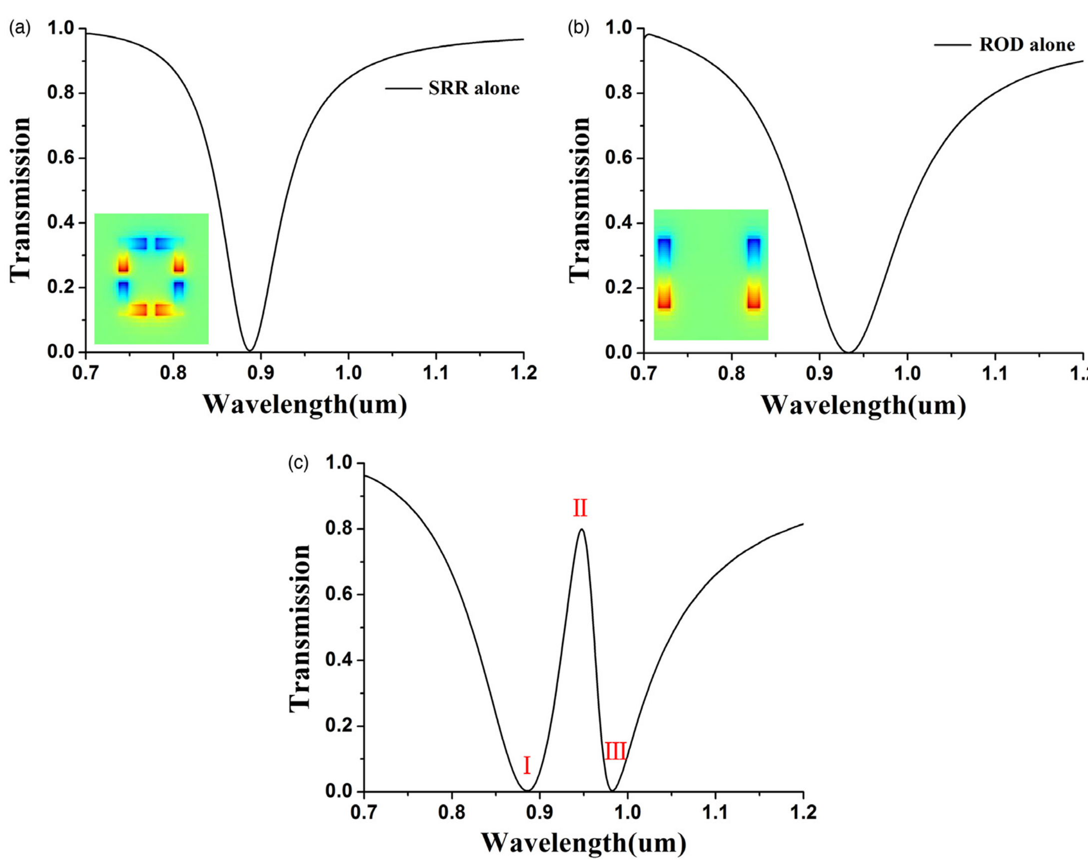

Fig. 2. The transmission spectra and electric field distribution for (a) the SRR and (b) the two metal strips at normal incidence with E along y axis (c) The transmission spectra of the symmetry structure.