Optical Materials 52 (2016) 14–20

Contents lists available at ScienceDirect

Optical Materials

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

Plasmon-induced transparency in the plasmonic nanostructures composed of C-shaped metal and ellipsoid strip

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ARTICLE INFO

Article history:
Received 7 November 2015
Received in revised form 25 November 2015
Accepted 29 November 2015
Available online 12 December 2015

Keywords:
Surface plasmons
Transmission spectra
Plasmon-induced transparency
Field distribution

ABSTRACT

We investigate numerically the plasmon properties supported by bright–dark resonators and bright–dark–bright resonators composed of C-shaped metal and metallic ellipsoid strip by using the finite difference time domain (FDTD) method. The plasmon-induced transparency (PIT) effect in the nanosystem is associated with the destructive interference between the dark and bright modes. In comparison, bright–dark–bright resonators obtained more prominent transparency windows than bright–dark resonators. And it is found that the transmission spectra of the nanostructures can be tuned by structural parameters of inner radius of the C-shaped resonator, the short-axis of the ellipsoid gold strip and the distance between the resonators. The electric and magnetic field distributions of certain resonance wavelengths are given to discuss the underlying physics.

1. Introduction

The surface plasmon polaritons (SPPs) have received much attention owing to the charming physics and significant applications such as biological or chemical sensing and fluorescence resonance energy transfer [1,2]. The interactions between two or more plasmonic structural unit lead to the fascinating plasmonic modes hybridization, which is able to modulate the resonance frequency of the plasmonic system. Plasmon hybridizations and interferences in the complex metallic nanostructures provide a powerful means to tailor the spectral response and reinforce local field at nanometer scale [3,4]. Recently, the combine of metamaterials and plasmonics areas has given rise to the accomplishment of negative refractive index metamaterials in the optical frequencies [5]. Furthermore, plasmonic nanostructures are found to be able to minimize optical components and achieve forceful nonlinear optical effects, which is owing to light manipulation on deeply sub-wavelength scale and the remarkable field enhancement [6].

A plasmon mode can be either dark mode (subradiant mode) or bright mode (superradiant mode) relying on how strong the plasmon mode can be coupled into the incident light from free space. The dark mode has higher quality factor but the bright mode possesses lower quality factor, which results in the analogy of the dark mode with a metastable level in an atomic system. The metastable energy level is needed for the realization of an electromagnetically-induced transparency (EIT) medium [7–9]. Although EIT has been observed initially in quantum mechanical systems [10], EIT-like effect can also achieve by plasmonic nanostructures which are usually called plasmon induced transparency (PIT) [7,11]. The PIT has attracted much attention due to the advantages in applications such as wide bandwidth and the underlying physics. Many researchers have paid efforts to pursuit PIT effect in metamaterials. The application of dipole antennas is a specific instance among the PIT studies [12,13]. Lu et al. [14] proposed a plasmonic structure which a unit cell composed of a parallel metal pair and a single metal strip, and they analyzed the underlying physics of PIT in the metamaterials. Tassin et al. [15] demonstrated theoretically that PIT can be achieved in a metamaterial consists of two coupled rectangle split-ring resonators (SRR). Kim et al. [16] investigated the electromagnetic response of the concentric multi-ring structure as an extension of the dual-ring metamaterial which exhibits PIT effect. In addition, a series of micro- and nano-structures such as SRR combines with nano-rods [17] and cut wires [18] have been shown to realize PIT effect. PIT actually provides the plasmonic modes beyond the fundamental ones are taken into account.

In fact, PIT effects are attributed to the interference of different pathways of electromagnetic fields. The underlying principle of PIT can be divided into two types: one is near-field coupling

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http://dx.doi.org/10.1016/j.optmat.2015.11.046
0925-3467/

mechanism and the other is phase-coupling mechanism. Zhang et al. [7] first proposed PIT in planar metamaterial consisting of bright and dark modes based on near-field coupling. He et al. [19] also designed a novel disk/rod hybrid metasurface to investigate an actively controlled PIT spectral response through polarization-dependent near-field coupling between the disk (bright) and the rod (dark) resonator. These near-field coupling schemes hinge on the strength of the coupling between the bright and the dark modes and require precise lithographic control [20]. To obviate the requirement of near-field coupling, Kekatpure et al. [21] demonstrated the existence of PIT spectral response in a system of nanoscale plasmonic resonator antennas coupled by means of a single-mode silicon waveguide. Their proposed scheme exploited the phase-coupling between the antennas in contrast with the plasmonic approaches that rely on the strength of direct, near-field coupling of nanometallic elements. Subsequently, Jin et al. [20] proposed a new scheme for a controllable PIT spectral response at microwave frequencies based on phase coupling between two identical SRRs with side-by-side symmetry. Recently, Zeng et al. [22,23] investigated multiple PIT effects in graphene metamaterials consisting of a series of self-assembled graphene Fabry–Pérot (FP) cavities based on phase coupling mechanism.

In this paper, we study numerically the PIT effects supported by the plasmonic nanostructures which are composed of C-shaped metal and metallic ellipsoid strip. In comparison, bright–dark–bright resonators obtained more prominent transparency windows than bright–dark resonators. The simulated numerical results also show that the transmission spectra of the compound structures can be tuned by structural parameters.

2. Structure and simulation method

Fig. 1 gives the schematic illustration of the proposed plasmonic nanostructure. The yellow background material indicates the metal gold. The C-shaped metal is called bright resonator, and the ellipsoid vertical metal strip is termed dark resonator. The bright–dark resonators and the bright–dark–bright resonators structures are depicted in Fig. 1(a) and (b), respectively. The outer and inner radii of the C-shaped bright resonator are denoted by R_1 and R_2. In the whole paper, we keep $R_1 = 50$ nm fixed. The lengths of the long-axis and short-axis of the ellipsoid gold strip are labeled $2R_1$ and S. That is, the heights of the dark and bright resonators are consistent. The horizontal distance between the left C-shaped resonator (LCR) and the dark resonator is d_1, and the distance between the dark resonator and the right C-shaped resonator (RCR) is d_2. All the proposed compound nanostructures are immersed in a vacuum.

The two-dimensional finite-difference time-domain (FDTD) method is employed to solve Maxwell's equations [24]. As shown in Fig. 1, the nanostructure is illuminated by a normal incident Gaussian single pulse wave with propagation vector ($\vec{k}$) along the x-direction, electric field vector ($\vec{E}$) along the y-direction. The analyzed structure is simulated by an FDTD cube of size $L_x \times L_y = 800$ nm $\times$ 400 nm and infinity along the z axis. The spatial and temporal steps are set as $\Delta x = \Delta y = 1$ nm, and $\Delta t = \Delta x/2c$ (c is the speed of light in vacuum). Also, perfectly matched layer (PML) absorbing boundary condition and periodic boundary condition are applied along the x and y-axes, respectively.

The frequency-dependent dielectric constant ε_m of gold is given approximated by the Drude model as [25,26]:

$$\varepsilon_m(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma_p} \tag{1}$$

where ω_p denotes the bulk plasma frequency of metal, ω is the angle frequency of the incident wave and γ_p represents the collision frequency, respectively. The dielectric constant of gold is taken from Ref. [27].

3. Results and discussion

3.1. The bright–dark resonators

Firstly, Fig. 2(a)–(c) present the transmission spectra of the plasmonic nanostructure with only C-shaped resonator, only ellipsoid gold strip and both bright and dark resonators comprised, respectively. Here, the geometric parameters $R_2 = 30$ nm, $d_1 = 40$ nm and $S = 20$ nm are fixed. On the one hand, the C-shaped resonator is analogous to a bright mode resonator for a broad linewidth of the resonance dip in the transmission spectrum (as shown in Fig. 2(a)). The bright mode is formed by the strong coupling between the SPPs and the external electromagnetic wave. On the other hand, the ellipsoid gold strip is taken as the dark mode resonator with a narrow linewidth of the resonance dip (as shown in Fig. 2(b)). The narrower dip implies the resonator couples weakly with incident wave and has a long lifetime, which can be regarded as a dark mode in the PIT. The dark mode is formed by the near-field interaction with the fields of the bright mode [28], since it cannot be excited by the external field at normal incidence [29] because of its vanishing dipole moment and/or bianisotropy [30]. The two resonance dips are located at wavelength $\lambda = 0.4807$ µm and $\lambda = 0.4132$ µm in visible region. When these two resonators are synthesized to one plasmonic system, the compound nanostructure achieves the requirements of the PIT system

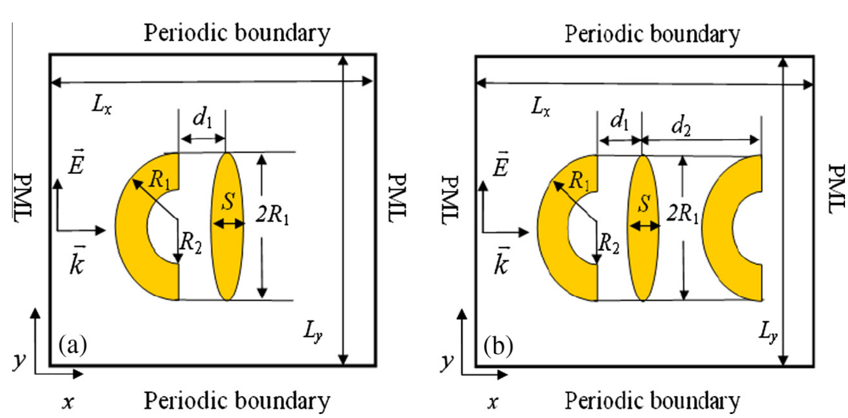

Fig. 1. x–y cross section of the periodic compound nanostructure composed of (a) dark–bright resonators and (b) dark–bright–dark resonators. Parameters are defined in the text.