Optik 126 (2015) 541–544

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Electromagnetically induced transparency in a planar complementary metamaterial and its sensing performance

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ARTICLE INFO

Article history:
Received 22 January 2014
Accepted 16 January 2015

Keywords:
Complementary metamaterial
Electromagnetically induced transparency
Sensor

ABSTRACT

In this paper, a classical analogue of electromagnetically induced transparency (EIT) is demonstrated theoretically in a planar complementary metamaterial consisting of a short slot as bright resonator and a long slot as dark resonator in a thin sliver film. A sharp and narrow reflectance transparency window is observed within a broad absorption spectrum at optical frequencies when structural symmetry is broken. Furthermore, the transparency peak exhibits highly sensitive response to the refractive index of surrounding medium, ensuring our proposed metamaterial as an excellent plasmonic sensor. The dependence of figure of merit (FOM) on structural asymmetry is investigated numerically to optimize the sensing performance of the EIT-based sensor.

1. Introduction

Electromagnetically induced transparency (EIT) is a quantum phenomenon, which comes from quantum interference of different excitation pathways though short and long-lived resonances in an atomic system and gives rise to a spectrally narrow optical transmission accompanied with extreme dispersion in the absorption spectrum [1,2]. Due to this drastic modification of the dispersive properties of the medium, EIT effect has been extensively applied to nonlinear optics, such as slow light [3], enhanced optical nonlinearities [4], optical delay lines [5], and sensing [6]. However, limited material choices and stringent requirements to preserve the coherence of excitation pathways in atom systems have significantly constrained the application of EIT effect. Recently, plasmonic analogues of EIT in metamaterial structures have attracted tremendous attention since the EIT-like metamaterials not only avert the scathing experimental requirements of quantum optical implementation, but also take advantage of the effective medium characteristics of metamaterial [7–10].

Owing to their remarkable confinement of electromagnetic field near the plasmonic nanostructures and spectrally narrow linewidth at the transparency window, EIT-like metamaterials are considered as a greatly promising candidate in biological and chemical sensors [11,12]. However, as far as we are aware, most of metamaterials consist of nano-particles unit cells, which lead to difficultly bond the sensing medium with the sensing component of sensors. Recently, based on Babinet's principle, some complementary metamaterials have been designed to achieve EIT-like resonances in reflectance spectrum for sensing application [13,14].

In this letter, a plasmonic analogue of EIT effect is demonstrated theoretically in a planar complementary metamaterial consisting of a short slot and an elongated slot in a thin sliver film. The short slot is functioned as an optical antenna, serving as the radiative role, and the elongated one supports a high-order multipolar plasmon resonance, thus acting as the sub-radiative role. The destructive interference between them gives rises to a pronounced electromagnetically induced reflectance transparency window within a broad resonance spectrum in the optical region. Based on this special optical property, the sensitivity and the corresponding figure of merit (FOM) of metamaterial sensor are investigated in detail by changing the refractive index of surrounding medium. In addition, the influences of structural asymmetric on the sensing performance of EIT-based sensor are also investigated.

2. EIT-like effect in the planar complementary metamaterial

Generally, a simple metal nano-strip can be function as an optical antenna due to its dipolar localized surface plasmon resonance (LSPR) [15]. In accordance to Babinet's principle, its complementary structure, a slot in a metallic film [13], can also achieve the

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http://dx.doi.org/10.1016/j.ijleo.2015.01.006
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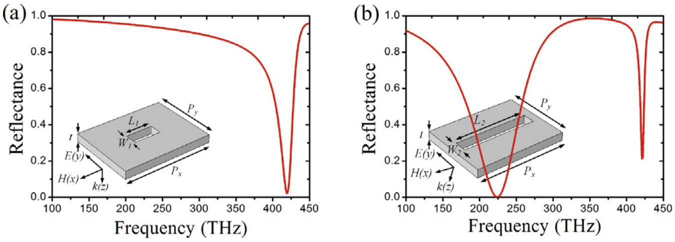

Fig. 1. (a) Reflectance spectrum of a short sliver slot which functions as a bright antenna. Inset: Schematic diagram of the slot structure and the incident light polarization. The geometric parameters W_1, L_1, and t are 40, 130, and 20 nm, respectively. A plane wave is incident along the z direction, with H along the x directions. In all simulations, the periodicity is set to be 440 nm in both x and y directions. (b) Reflectance spectrum of an elongated sliver slot which functions as a dark antenna. Inset: Schematic diagram of the slot structure and the incident light polarization. The geometric parameters W_2, L_2 are 40 and 360 nm, respectively. The incident wave vector lies in the x–z plane and is tilted 45° from the z direction, with the electric field along the y direction.

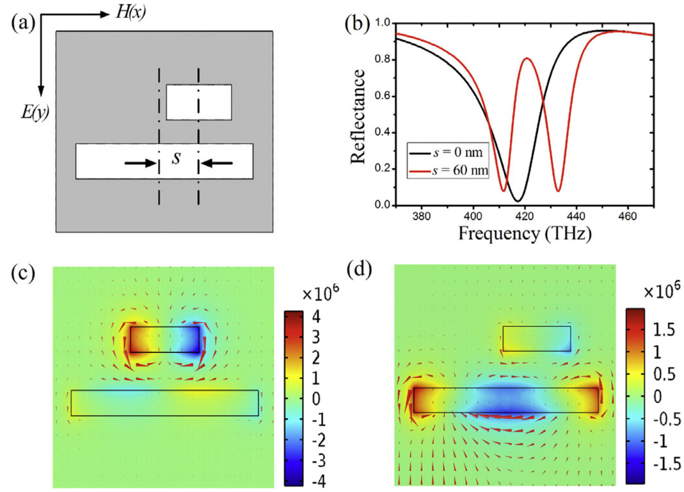

Fig. 2. (a) Top view of our proposed complementary metamaterial consisting of a radiative element and a dark element, with light incident in the normal direction. The lateral displacement of the short slot with respect to the symmetry axis of the long bar is s. (b) Reflectance spectra of the metamaterials for symmetric structure s = 0 nm and asymmetric structure s = 60 nm. (c) Distribution of magnetic field and current at reflectance dip for symmetric structure. (d) Distribution of magnetic field and induced current at reflectance transparent peak for asymmetric structure.

goal of a radiative resonator (inset of Fig. 1(a)). Fig. 1(a) shows the reflectance spectrum of the slot antenna, which is coupled to a normal incident light with the magnetic field along the slot. The numerical calculations are carried out by solving Maxwell equations using the finite difference time domain (FDTD) [16]. The metal material is selected as sliver due to its low intrinsic loss in the optical regime. The permittivity of sliver is described by the Drude model with the plasma frequency $\omega_p = 1.366 \times 10^{16}$ rad/s and the damping constant $\gamma = 3.07 \times 10^{13}\ \mathrm{s}^{-1}$ [7]. It is seen that there is a resonant dip in the reflection spectrum. The origin of this resonance is attributed to the excitation of dipolar plasmon in the slot, which mainly suffers seriously radiative losses, resulting in a low Q-factor, namely bright mode.

Because of structural symmetry, the high-order LSPR modes cannot be directly excited by the filed of normally incident radiation. By changing an angle of 45° with respect with to the x direction in the x–z plane [17], when an external electromagnetic field irradiates an elongated sliver slot, two resonances with different Q-factor are observed in the reflectance spectrum as shown in Fig. 1(b). Compared with their line-widths, it is easily deduced that the resonance peak at frequency 225 THz origins from the radiative dipolar plasmon mode and that the resonance peak at 421 THz arises from the sub-radiative quadrupolar plasmon mode, which solely suffers from the intrinsic metallic losses (Drude damping) and results in a high Q-factor, namely dark mode. Compared with the linewidth of both slots, the Q-factor of the elongated slot is distinctly larger than that of the short one.

In order to generate EIT-like response in a planar plasmonic metamaterial, two slots with different length are arranged in a thin sliver film, as illustrated in Fig. 2(a). In this cut-out system, the short slot can be excited directly by incident light and serves as a bright element, and the elongated one serves as a dark one, which is coupled to the bright antenna by mean of near-field plasmon hybridization. Fig. 2(b) shows the simulated reflectance spectrum of our proposed complementary metamaterial at optical frequencies. In the absence of structural asymmetry (s = 0 nm), there is only one broad resonance (about 418 THz) observable in the reflectance spectrum, which originates from the excitation of dipolar surface mode inside the short slot. The distributions of the magnetic field (see Fig. 2(c)) intuitively display the excitable pattern of slot dipolar LSPR and well agree with the origin of this resonance. Due to the mirror effect in the long slot, the resonance position of the dipole mode has some redshift with respect to that of only one slot (about 421 THz).

When displacing the short slot along the elongated one, that is, symmetry breaking [8,17], a pronounced reflectance peak with a large Q-factor appears within the background spectrum of the broad dipolar-like resonance for the case of s = 60 nm as shown in Fig. 2(a). We interpret the above phenomena as a plasmonic analogue of EIT phenomenon in the reflectance spectrum. For the case of s = 0 nm, due to lack of structural asymmetry, the dark mode of the long slot can not be excited by normally incident light nor by the coupling to the bright oscillator through near-field interaction, thus the spectrally responded pattern of symmetric structure presents only one broad resonance. When symmetry is broken, it will be possible that the bright and dark antennas interact with each other, and as a result, destructive interference between two excitation pathways, namely, the direct excitation of the dipole antenna by the external light and the excitation by coupling with the quadrupole antenna, leads to transparency window in the reflectance spectrum. To further support the above assertion, the distributions of the z-component of magnetic field at the transparent peak 421 THz is shown in Fig. 2(d). It is obviously seen that the quadrupole mode of the dark antenna is strongly excited, and the antisymmetric charge oscillations in both long sides of the long slot suggest that this mode has no dipolar moment and solely is restricted by the intrinsic Drude losses of metal. Meanwhile, because the destructive interference between both pathways suppresses the dipolar polarization of the bright antenna, it leads to no electromagnetic enhancement in the void of the short slot.

3. Refractive index sensing based on EIT-like effect

Due to the EIT-like narrow window and strongly electromagnetic enhancement at resonance and the special cut-out structure, they render complementary EIT-like metamaterials distinct superiority in refractive index sensing. Here we evaluate the sensing performance of our proposed EIT-like metamaterial in the optical region by measuring the spectral shift of the sensor surrounded in different dielectric conditions. Fig. 3(a) shows the calculated reflectance spectra of the asymmetric structure (s = 60 nm) in air and dielectric with n = 1.02, 1.04, 1.06, respectively. A clear shift of the reflectance spectra peak to low frequency is visible when increasing the refractive index of the sensing medium from 1 to 1.08. This characteristic infers that the resonance responses of plasmonic resonators sensitively depend on the surrounding medium [18]. In order to apparently express the sensing property of our