Highly-dispersive transparency at optical frequencies in planar metamaterials based on two-bright-mode coupling

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Abstract: Using a planar metamaterial, which consists of two silver strips, we theoretically demonstrate the plasmonic electromagnetically-induced transparency (EIT)-like spectral response at optical frequencies. The two silver strips serve as the bright modes, and are excited strongly by the incident wave. Based on the weak hybridization between the two bright modes, a highly-dispersive plasmonic EIT-like spectral response appears in our scheme. Moreover, the group index is higher than that of another scheme which utilizes the strong coupling between the bright and dark modes.

OCIS codes: (160.3918) Metamaterials; (260.5740) Resonators; (260.2110) Electromagnetic optics.

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Metamaterial is a kind of artificially-fabricated materials, which has been studied by many researchers recently owing to its well-controlled properties of incident electromagnetic waves, such as negative index materials [1], extraordinary optical transmission [2–5], classical analogue of electromagnetically-induced transparency (EIT) [6–27], and so on. Realization of the

EIT-like effect was usually achieved by using two kinds of schemes: the bright-dark mode [7–20] coupling and the bright-bright mode [21–27] coupling. Zhang *et al.* [10] firstly proposed a plasmonic EIT in planar metamaterial based on the near-field coupling between bright and dark modes. Subsequently, using a stacked optical metamaterial consisting of the bright-dark modes separated by a dielectric spacer, Liu *et al.* [11] experimentally demonstrated the plasmonic EIT at the Drude-damping limit. The scheme of stacked optical metamaterial somewhat overcomes the requirement of a precise lithographic control, but it is still not easy to fabricate compared to the planar metamaterial. Based on the phase coupling between two bright modes, Kekatpure *et al*. [27] proposed the analogue of plasmonic EIT at optical frequency in a system of nanoscale plasmonic-resonator antennas coupled by means of a single-mode silicon waveguide. Recently, using two split-ring resonators, serving as the bright modes, several schemes of the analogue of EIT were proposed in the microwave [21, 23], the THz [24] and the optical ranges [25].

In this work, based on the weak hybridization between two bright modes, we propose a new scheme for the generation of plasmonic EIT-like spectral response at optical frequency in planar metamaterial which consists of two silver strips (see Fig. 1). Because the weak coupling between two silver strips induces a highly-dispersive transparency peak, a large group index is obtained, based on the trapped mode in our scheme.

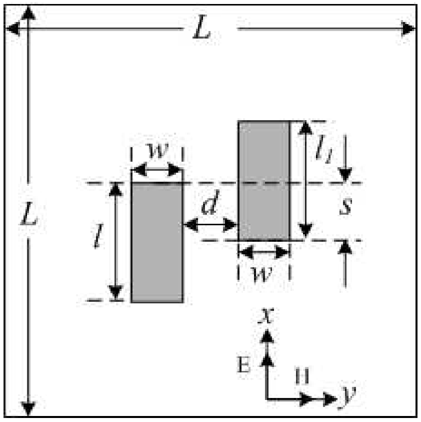

Fig. 1. Top views of the unit cell.

Figure 1 presents the schematic of the plasmonic EIT-like structure we have investigated. The unit cell consists of two silver strips serving as the bright modes. The geometric parameters are w = 65, d = 70, and l_1 = 150 nm. Displacement s and length l are variable. The thickness t of each strip is 20 nm. The periodicity L are 520 nm in both x and y directions. The incident plane waves are irradiated along the z direction, and its electric component, **E**, is parallel to the x direction. In our structure, the two silver strips are strongly excited by the incident plane wave. The permittivity of silver is described by the Drude model, with a plasmon frequency ω_p of 1.366×10^{16} rad/s and a collision frequency ν_c of 3.07×10^{13} Hz [10, 28]. The numerical calculations are carried out by using a finite-integration package (CST Microwave Studio).

The two silver strips serve as optical dipole antennas that can be excited by the incident plane wave, and strongly induce the localized electric and magnetic fields in our scheme. The excited optical dipole antennas interact with each other, and the strength of the interaction between the two silver strips can be controlled by parameter s. It should be noted that the parameter s is enough to characterize the dipolar coupling strength. In the dipolar-coupling mode [30, 31], the dipolar-coupling strength, which determines the splitting of resonance mode, can be

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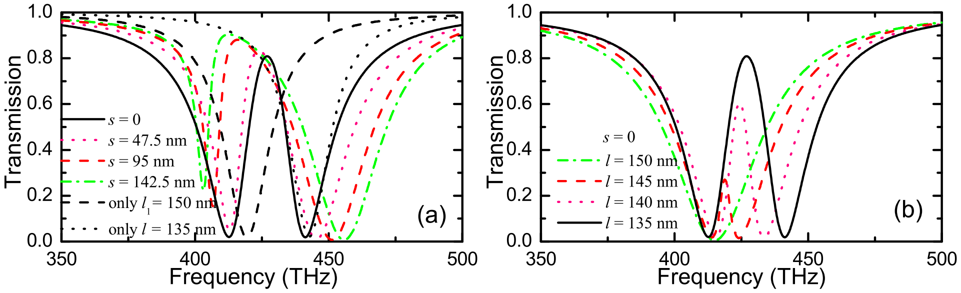

Fig. 2. (color online) (a) Dependence of simulated transmission spectra on displacement s with $l = 135$ and $l_1 = 150$ nm. (b) Dependence of simulated transmission spectra on length l when $s = 0$.

characterized by the displacement vector $\vec{R}$ and the angle θ between the direction of dipole and $\vec{R}$. In our case, the distance between two strips is fixed, the single parameter s is enough to determine $\vec{R}$ and θ. This interaction results in the splitting of a plasmon resonance into two new resonances (the bonding and the antibonding modes). This plasmon-resonance-hybridization scheme [29] gives intuitively an electromagnetic analog of molecular-orbital theory.

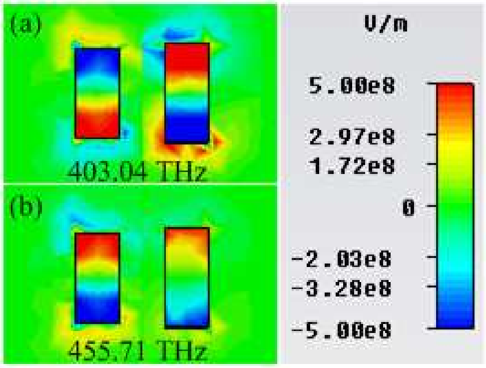

Fig. 3. (color online) z-component distribution of electric fields at resonance frequencies (a) 403.04 and (b) 455.71 THz when $s = 142.5$ nm.

Figure 2(a) presents the simulated transmission spectra at optical frequencies according to displacement s. The black dotted and dashed lines show the simulated transmission spectra of single silver strip only with $l = 135$ nm and $l_1 = 150$ nm, respectively. The green dot-dashed, the red dashed, the pink dotted and the black solid lines indicate the simulation transmission spectra for various s from 142.5 nm to 0 with an decrement of 47.5 nm, when lengths l and l_1 are 135 and 150 nm, respectively. From Fig. 2(a), we can see that two new resonance modes at 403.04 and 455.71 THz are obtained when $s = 142.5$ nm, which are shifted from the initial resonance frequencies of 419.37 and 442.83 THz, based on the plasmon hybridization. With decreasing s, the low-energy peak is broadened, while the high-energy one becomes narrower, and the width of transparency peak becomes smaller. This is because the displacement s comes to be smaller, so the two resonance modes are weakly hybridized. When s decreases to be zero, two resonance modes (412.7 and 441.22 THz) approach the respective resonance frequencies when there only a single silver strip exists. Figure 2(b) shows the simulated transmission spectra according to length l of the left strip when $s = 0$. The green dot-dashed, the red dashed, the pink dotted and the black solid lines present the simulation transmission spectra for various lengths l of the strip from 150 to 135 nm with an decrement of 5 nm. When lengths $l = l_1 = 150$ nm, only one resonance peak appears because two silver strips have the same phase and resonance mode. With decreasing length l, the transparency peak widens and its strength enhances at the same time.

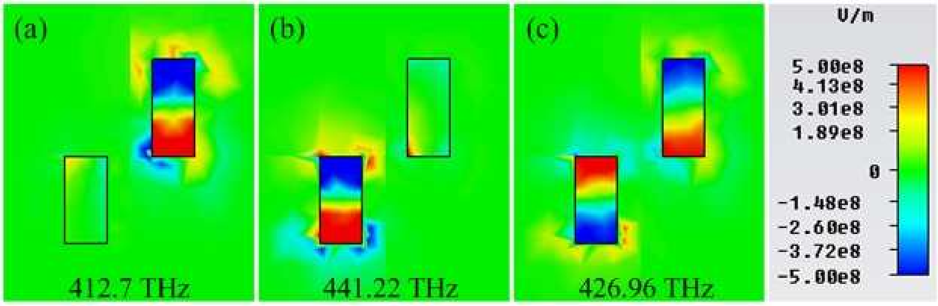

Fig. 4. (color online) z-component distribution of electric field at frequencies of (a) 412.7, (b) 441.22 and (c) 426.96 THz when $s = 0$.

To further support the above assertion, the distribution of z-component of electric field is shown in Figs. 3 and 4 for normal-incident plane wave. The distributions of z-component of electric field are shown in Figs. 3(a) and 3(b) for a phase of 315° at a frequency of 403.04 and 455.71 THz, when $s = 142.5$ nm, respectively. From Figs. 3(a) and 3(b), we can see that the excited two silver strips are coupled strongly with each other, leading to two new resonance modes deviated from the initial frequencies (419.37 and 442.83 THz), according to the plasmon-resonance hybridization [29]. The low-energy (403.04 THz) and the high-energy (455.71 THz) modes exhibit the induced-current in opposite directions and the same induced-current directions in the two silver strips, analogous to the bonding and the antibonding modes in a hybridized-molecular system [29], respectively. Since the induced-current directions of two silver strips are opposite, the bonding mode is similar to the quadrupole mode and hence is narrow, as shown Figs. 2(a). On the contrary, since the induced-current direction in two silver strips are the same, the antibonding mode is broad. The coupling between the two silver strips is weak with decreasing s. When $s = 0$, the excited two silver strips are very weakly hybridized, and two resonance modes (412.7 and 441.22 THz) are close to their initial frequencies as shown in Figs. 4(a) and 4(b). Figure 4 displays the distributions of z-component of electric field for a phase of 315° at two resonance peaks and one transparency peak, when $s = 0$. When frequency is 412.7 THz, only the right silver strip is excited strongly by incident light, and the left silver strip is excited very weakly, as shown in Fig. 4(a). On the contrary, only the left strip is excited by incident light strongly, and the right strip is excited very weakly when frequency is 441.22 THz, as shown in Fig. 4(b). At 426.96 THz, both silver strips are excited simultaneously owing to the resonance detuning, and the induced currents of two strips are out of phase by 180°, which is the characteristics of electromagnetically-trapped mode, as shown in Fig. 4(c). Because of the opposite current oscillations of two strips, the electric dipole moments of both elements can be canceled with each other, so that the scattered fields produced by these opposite currents are very weak. Therefore, the high transparency peak appears at 426.96 THz in our scheme. For example, in Fig. 4(c) the oscillation of the induced current and the near field of right strip excited by incident plane wave are opposite to those of the left strip. Therefore, the electric dipole moment of left strip is negligible. The same argument can be applied for the dipole moment of right strip. Moreover, because of the detuning of resonance frequency, the strength of induced electric field of two strips at the transparency peak 426.96 THz is very weakly smaller than that of the dipole-moment resonances at 412.7 THz and 441.22 THz, as shown in Fig. 4. This nearly unnoticeable difference is due to the small difference between the absorption at 426.96 THz and those at two transmission dips. Our simulated absorption spectrum (not shown) exhibits a small difference between the absorption at 426.96 THz and the other two. The relatively significant absorption at 426.96 THz is ascribed to a very weak scattered field, resulting in a low reflection and, in turn, a significant absorption.

Dependence of the group index and the maximum transmission at the transparency peak on length l is shown in Fig. 5. The maximum transmission at the transparency peak decreases evidently with increasing l. On the contrary, the group index at the transparency peak increases with increasing l up to $l = 146$ nm, where the maximum group index of 97 is observed, and then decreases. The group index n_g is estimated according to formula $n_g = n + \omega(dn/d\omega)$, where n is the effective refractive index [32]. In our scheme, using the weak coupling between two bright modes, we obtain the group index twice larger than that obtained by using the coupling between bright and dark modes [10] with the same transmission. For example, when the transmission is -3.3 dB $\approx$ 0.47, the group index is less than 20 in Ref. [10], however, in our scheme, the group index is $\sim$ 50 for nearly the same transmission.

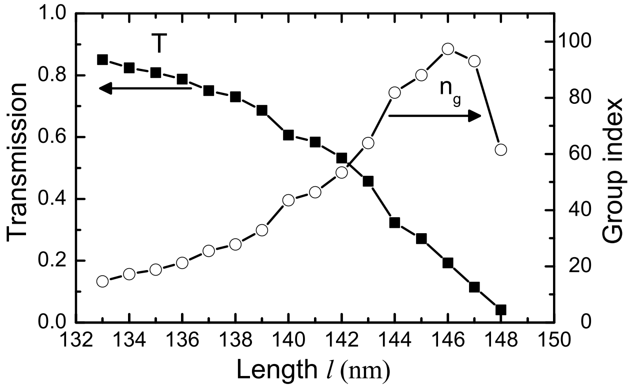

Fig. 5. Dependence of both group index and maximum transmission on length l.

In conclusion, using the planar metamaterial, which consists of two silver strips, we propose a new scheme for the plasmonic EIT-like spectral response at optical frequencies. Because the coupling between two bright modes induces highly-dispersive transparency, the higher group index can be achieved in our scheme than the coupling between bright and dark modes [10].

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