Plasmonic Analogue of Electromagnetically Induced Transparency in Detuned Nano-Cavities Coupled to a Waveguide

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Abstract We theoretically investigate the classical analogue of electromagnetically induced transparency (EIT) in a plasmonic structure constituted by double side cavities connected symmetrically to a waveguide. The EIT is demonstrated by simply detuning the sizes of the two cavities (i.e., the length difference ΔL, keeping their width w similar). The physical mechanism behind the EIT resonance is unveiled as being caused by the destructive and constructive interference between the confined modes in the two cavities. The former play the role of two coupled radiative oscillators. The proposed structure may have important applications for designing integrated devices such as: narrow-frequency optical filters, novel sensors and high-speed switches.

Keywords Electromagnetic induced transparency · Surface plasmon-polariton · Cavity resonator

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1 Introduction

Electromagnetically induced transparency (EIT) is a quantum interference phenomenon that renders an opaque medium transparent in a narrow spectral region with low absorption and steep dispersion [1, 2]. These properties have been exploited to show different applications in these systems such as: slow light, sensing and data storage [2, 3]. However, it was realized that EIT-like behaviors are not uniquely associated to quantum systems and can be extended to classical systems [2, 3]. In this context, several classical systems have been designed to demonstrate the classical analogue of EIT. Among these systems one can cite: plasmonic nanostructures [4–7], planar metamaterials [8, 9], photonic crystal waveguides coupled to cavities [10–12], coupled microresonators [13–16], micro and radiowave circuits [17–19] and acoustic slender tube waveguides [20, 21].

As concerns plasmonic systems [4–9], metamaterials made of split-rings and cut-wires as well as plasmonic waveguides with coupled cavities have shown EIT and Fano [22] resonances with high quality factors. Due to their deep subwavelength confinement of light at the metal-dielectric interface, plasmonic materials have been suggested as an alternative to overcome the classical diffraction limit and manipulation of light in nanoscale domain [23]. The EIT resonance can be obtained using two coupled resonators (or oscillators) with closely spaced frequencies. The resonators with high (dark resonator) and low (radiative resonator) Q factors give rise to the so-called Λ-type configuration [1] in three atomic levels, whereas the resonators with low Q factors (radiative resonators) give rise to the so-called V-type configuration [4, 6, 18–21]. The latter mechanism has been demonstrated in little works in comparison with the first one.

In few recent works, the V-type resonances in double stub resonators connected at the same site along a waveguide have been shown in plasmonic [4, 6], photonic [18, 19] and acoustic [20, 21] materials. The case of two plasmonic cavities interacting with a waveguide by means of evanescent waves (near field mechanism) through a metal gap, has been shown by Zhang et al. [24]. They have studied numerically light propagation in a metal-air-metal waveguide and two side-coupled cavities located at a symmetric position around the waveguide. The two cavities are characterized by the same size but with different dielectric permittivities. They have shown the possibility of the existence of plasmonic EIT resonance that can be detuned by varying the dielectric permittivities in the two cavities. This study has been implemented by calculating the transmission amplitude through the system using the finite difference time domain (FDTD) method. In this work, we studied numerically the plasmonic analogue of EIT in a two side-coupled cavities to a waveguide. The optical properties of the modeled structure such as transmission, reflection and absorption spectra are obtained using finite-element method (Comsol Multiphysics Package) [25]. The waveguide and the cavities are embedded in a metal and filled with air. Also, we consider that both cavities have the same width (w = 100 nm), whereas their lengths L_1 and L_2 can be detuned. We show the

Fig. 1 Structure of the plasmonic nanoscale resonator system
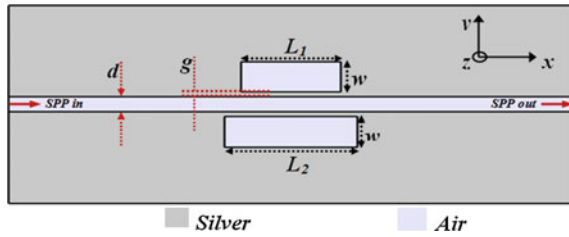
possibility of existence of EIT resonance by detuning the size of the two cavities (Fig. 1). Their separation from the waveguide is referred to as g (metallic gap that enables evanescent coupling).

2 Numerical Results

In our model the dielectric function of the metal (silver) is described by the lossy Drude model whose parameters are: $\varepsilon_\infty = 12.5$, $\omega_p = 2.05 \times 10^{16}$ rad/s and $\Gamma = 10^{14}$ rad/s [26]. The waveguide width, d, is equal to 50 nm, and the incident plane wave is a TM polarized one. In order to show the possibility of existence of EIT-resonance, i.e. a resonance squeezed between two transmission zeros, we have to take L_1 and L_2 slightly different. An example corresponding to this situation is given in Fig. 2a (pink curves) for $L_1 = 240$ nm and $L_2 = 258$ nm (i.e., $\Delta L = L_2 - L_1 = 18$ nm). One can notice the existence of deep dips in the transmission spectra around $\lambda_1 = 654$ nm and $\lambda_2 = 693$ nm and a resonance peak (transmission window) is induced at $\lambda_r = 672$ nm between the dips. The resonance does not reach unity because of the absorption in the system (see Fig. 2c), the reflection being very weak (Fig. 2b). As a matter of comparison, we have also plotted the transmission, reflection and absorption for each resonator alone (black and red curves).
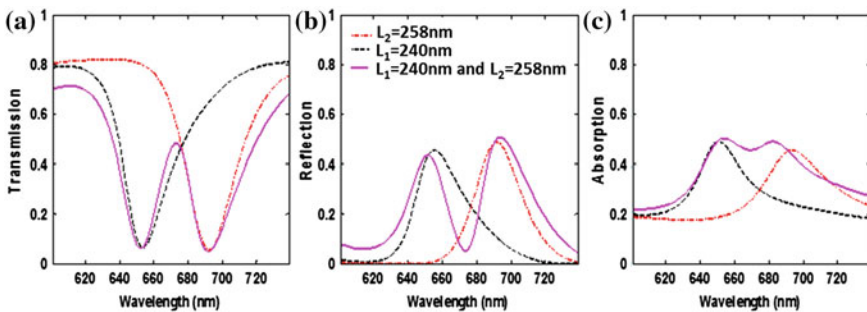

Fig. 2 **a** Transmission spectra when a single cavity is coupled to the waveguide with $L_1 = 240$ nm (*black curve*) and $L_2 = 258$ nm (*red curve*). The *pink curve* corresponds to the case when both cavities are present in the system ($L_1 = 240$ nm and $L_2 = 258$ nm). **b** The same as in (**a**) but for the reflection. **c** The same as in (**a**) but for the absorption
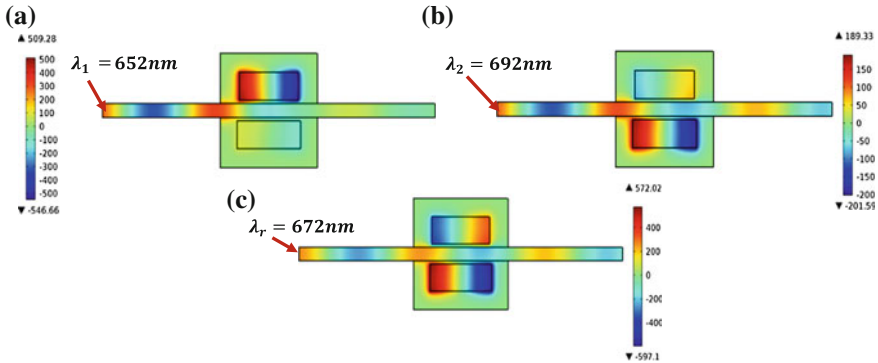
Fig. 3 **a**, **b** Magnetic field map at transmission dips around $\lambda_1 = 652$ nm and $\lambda_2 = 692$ nm respectively. **c** The same as in (**a**) and (**b**) but for the resonance peak around $\lambda_r = 672$ nm

One can notice that the transmission zeros are induced by each cavity [27], whereas the resonance is a consequence of the constructive interference between cavities. In order to show the spatial localization of the different modes in Fig. 2, we have plotted in Fig. 3 the amplitude of the magnetic field map at the two dips around $\lambda_1 = 654$ nm (Fig. 3a) and $\lambda_2 = 693$ nm (Fig. 3b). As predicted, the magnetic fields are mainly confined in each cavity and do not propagate in the system. These results are in accordance with those in Fig. 2a where the trapping and the rejection of the incident light wave is induced by the two cavities [27]. Around the resonance at $\lambda_r = 672$ nm (Fig. 3c), one can notice that both cavities are excited and the wave is transmitted along the waveguide as mentioned above. Therefore, the EIT resonance is a consequence of the constructive interference between the waves in the two cavities. However, the field is more localized in the lower cavity compared with upper one, which indicates that the latter is a bit less excited than the former. This is actually related to the asymmetry of the transmission spectra in Fig. 2a (pink curve) where the resonance peak wavelength is closer to the lower cavity eigenmode resonance wavelength than to the upper cavity. On the other hand, the field map shows that the excited cavities modes oscillate out of phase; this effect has been also observed in microwave photonic circuits [17–19].

3 Conclusion

In this paper, we have demonstrated numerically the possibility of existence of plasmonic analogue of EIT in metal-air-metal waveguide coupled to two nano-cavities filled with air but with different sizes. The waveguide and the cavities are embedded in a metal and the interaction between the incident light wave and the cavities occurs by means of evanescent waves through a small metal gap. We have shown (not presented here) that the behavior of the EIT resonance in the

transmission, reflection and absorption can be detuned by means of the difference in the size of the two cavities (depending of the value of the metallic gap g). These results may have important applications for designing integrated devices such as: narrow-frequency optical filters, novel sensors and high-speed switches.

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