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Plasmon induced transparency in a dielectric waveguide

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A classical effect of electromagnetically induced transparency (EIT) is demonstrated in a dielectric slab waveguide at visible frequencies. Two nano-sized elliptical silver particles are placed inside the waveguide core layer, and their localized plasmonic resonances are utilized to obtain bright and dark states. The destructive interference between the two resonance paths leads to an EIT-like transmission spectrum of the waveguide. The contrast between the transmission peak and dip can be further enhanced by incorporating the Fabry-Perot resonance effect. The influence of Joule loss on the EIT performance is also investigated. © *2011 American Institute of Physics*. [doi:10.1063/1.3621860]

Electromagnetically induced transparency (EIT) observed in atomic media is a quantum coherent process.[1] The transmission spectrum exhibits a narrow transparency window when a pumping light is present. The group velocity of a probing optical pulse may be greatly reduced as a result of very steep dispersion. A slowing-down factor up to seven orders can be achieved by employing the EIT technique.[2] However, applications based on quantum EIT are severely limited by the demanding conditions required to preserve electronic coherence. Thus, classical analogy of quantum EIT is highly desired, and various designs have been suggested. In Ref. 3, the EIT-like phenomenon inside a dielectric micro-sized system has been suggested and experimentally verified, which arises from the coupling between waveguides and resonators. Recently, metallic subwavelength micro-structures that mimic the EIT phenomenon have also been proposed.[4,5] In Refs. 4 and 5, bright and dark resonant states are constructed in metamaterial cells at the same time, and their coupling leads to the EIT transparency window in the transmitting spectrum when a plane wave impinges on the metamaterial. In Ref. 6, two plasmonic elements with slightly different resonant frequencies are coupled with each other by the guided mode of a waveguide, and subsequently an EIT-like transparency window appears in the transmitting spectrum of the waveguide.

In order to achieve a classical analogy of quantum EIT, resonant elements should be carefully designed. It is well known that nano-sized metallic particles could respond strongly to an incident light at the resonant frequencies, forming localized plasmonic resonance (LSP).[7] A metallic nano-particle may possess different resonant frequencies corresponding to different resonant orders.[8] For a low-loss metallic nano-particle, higher order resonance (e.g., quadrupole resonance) shows narrower resonant width, compared with lower order resonance (e.g., dipole resonance).[8] Moreover, the resonant frequencies of a metallic nano-particle can be tuned flexibly by changing its aspect ratio.[7,9] The localized plasmon resonance of metallic particles can occur not only in homogeneous surroundings, but also in complex surroundings such as waveguides and cavities. Resonance splitting of a plasmonic mode has been experimentally investigated inside a photonic crystal waveguide[10] and between metallic mirrors[11] recently.

In our current work, we would like to achieve an EIT-like phenomenon inside a single-mode dielectric slab waveguide in which the resonant elements (silver nanoparticles) are placed inside the core layer. In contrast to the previous EIT-scheme with a waveguide,[3,6] resonators located inside the core layer can interact more strongly with the guided mode since most of the energy is confined inside the high-index core layer. Localized surface plasmon resonance ensures a strong response although the resonator is of subwavelength size. Moreover, the dark state in the present work is achieved in a straightforward way.

As shown in Fig. 1(a), a symmetric single-mode slab waveguide is formed by using silicon nitride (Si_3N_4) as the core layer (refractive index $n = 2.03$, thickness $t = 160$ nm) and air as the background. Here, focus is put on the lowest-order transverse magnetic (TM) polarized guided mode with field components H_y, E_x, and E_z. In contrast to a transversely polarized plane wave, the TM guided mode has an additional longitudinal electric field component (E_z) due to the confinement of the dielectric waveguide. Component E_x is symmetric with respect to the x axis of the waveguide, and component E_z is anti-symmetric. Especially, E_z is exactly zero at the axis of

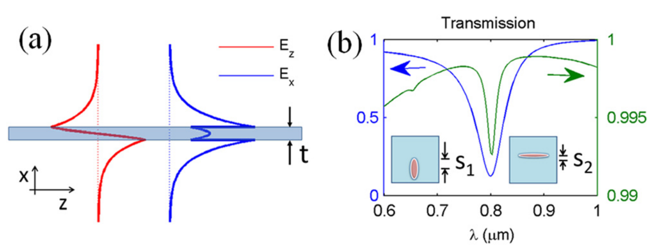

FIG. 1. (Color online) (a) Electric field component of the fundamental mode of a dielectric slab waveguide. (b) Transmission spectrum when elliptical silver particles are shifted from the waveguide centre axis. The blue line is for the transversely placed particle of $r_x = 36.4$ nm and $r_z = 6$ nm with shift $s_1 = 36.4$ nm and the green line for the longitudinally placed particle of $r_x = 5$ nm and $r_z = 63.5$ nm with shift $s_2 = 5$ nm. Here, r_x and r_z represent the semi-axis length of an elliptical particle along the x and z directions, respectively.

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the waveguide, which will be utilized to design a dark resonant state to achieve EIT-like transmission.

In our study, we first investigate the response of a single plasmonic particle embedded inside the Si_3N_4 core to the incident waveguide mode. Two kinds of elliptical silver particles, which have different aspect ratios and orientations, have been investigated here. Both of them possess large aspect ratios and then only respond to the electric field along their long axes within the interesting wavelength range (0.6–1 μm). One silver particle with a small aspect ratio is placed transversely and largely shifted from the core axis [see the inset on the left of Fig. 1(b)]. Its low-order localized plasmon resonance (dipolar resonance) is strongly excited in a broad wavelength range, and the incident guided mode is effectively blocked. In this sense, the particle is called a bright particle, and its dipole resonant mode serves as a bright state. Another silver particle has a larger aspect ratio, and it is placed longitudinally along the z axis. This particle has high-order localized plasmon resonance (quadrupole resonance) around the central wavelength 0.8 μm (of course, it has a low-order localized plasmon resonance, but the resonant frequency is much lower due to a larger aspect ratio). If it is placed exactly at the central axis of the waveguide, it cannot be excited by the guided mode due to the vanishing of the electric component E_z. In this sense, this particle is called a dark particle, and its quadrupole resonant mode serves as a dark state. To study its resonant properties, here this particle is slightly shifted from the waveguide axis to weakly excite the quadrupole resonance [see the inset on the right of Fig. 1(b)]. Fig. 1(b) shows the transmission spectrum of the waveguide containing the bright particle or the dark particle, respectively. The silver particles have been elaborately designed in physical size so that they possess the same central resonant wavelength (i.e., corresponding to wavelength 0.8 μm in vacuum). However, the bright particle exhibits strong broad-band resonance excitation (corresponding to dipole resonance), while the dark particle exhibits weak narrow-band resonance excitation (corresponding to quadrupole resonance). In calculation, the Drude model is used to describe the optical response of silver, namely, $\varepsilon_{Ag}(\omega) = 1 - \omega_P^2/[\omega(\omega + i\Gamma)]$ with $\omega_P = 2\pi \times 2.04 \times 10^{15}$ rad/s and $\Gamma = 2\pi \times 9.37 \times 10^{12}$ rad/s.[12] The numerical simulation is based on the finite-element method. An appropriate boundary condition is specified to ensure the excitation of single-mode guided wave. The normalized transmission of the waveguide is the ratio of the integrated energy flow at the output port to that at the input port.

Now, both of the above two plasmonic particles are placed into the single mode slab waveguide to realize EIT. The basic configuration is shown in Fig. 2(a). When the bright and dark particles approach each other, near-field coupling between them will take place, and EIT-like transmission is formed as shown in Fig. 2(b). Fig. 2(c) shows the electric amplitude distributions corresponding to the three characteristic wavelengths represented by A, B, and C in Fig. 2(b). The resonance characteristics of the bright and dark states can be clearly distinguished. The uniform electric field inside the transversely placed particle implies a dipole resonance, while the strong electric field at the left part and the right part inside the longitudinally placed particle indicates the excitation of two dipoles with opposite direction, i.e., a quadrupole. At the wavelengths λ_A and λ_C, the bright particle is effectively excited, and the excitation of the dark particle is fairly weak. Most of the incident guided energy is strongly scattered by the bright particle into the radiating mode and leaks out into the outside space. Thus, the transmission of the waveguide at wavelengths λ_A and λ_C is low as shown in Fig. 2(b). However, at wavelength λ_B, the accumulated charge at the upper end of the bright particle will induce strong quadrupole resonance of the dark particle, which serves as a dark state. Conversely, the strong excitation of the dark state may suppress the oscillation of the bright state in a destructive way. The interaction between the two different states eventually results in a weak excitation of the bright state and a strong excitation of the dark state [see the middle panel of Fig. 2(c)]. Therefore, a transmission peak occurs at wavelength λ_B as shown in Fig. 2(b).

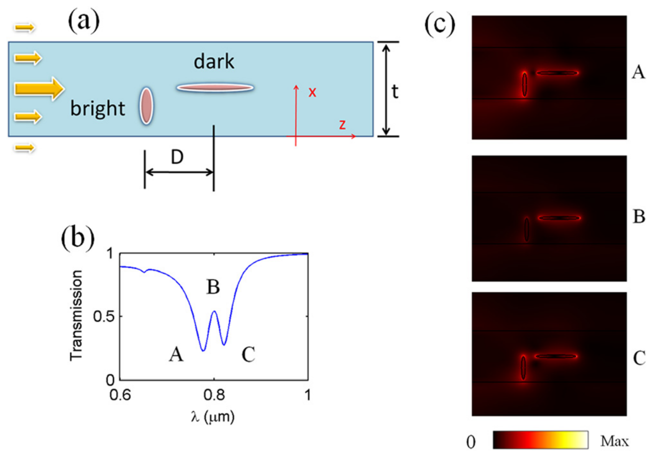

FIG. 2. (Color online) (a) Configuration for achieving EIT. All the parameters for the two particles are the same as in Fig. 1(a), except that s_2 is exactly zero in this situation. The centre-to-centre separation of the two particles is $D = 103$ nm. (b) Plasmon induced EIT transmitting spectrum of the waveguide. (c) Distributions of electric amplitude corresponding to the three wavelength values represented by A, B, and C, in (b).

It is widely recognized that an EIT-like phenomenon can be regarded as a special case of Fano resonance.[13] The peak value and line width of the EIT spectrum are closely related to the resonant properties of the bright and dark states and the coupling strength between them. Specifically, strong coupling strength will result in large transmission peak and broad transmission spectrum width and vice versa. In our configuration, the quadrupole resonance of the dark particle ensures narrow transmission spectrum width. Meanwhile, the separation D between the two bright and dark particles is chosen to be 103 nm to obtain moderate coupling for considerable transmission and narrow transmission spectrum width at the same time.

As can be seen in Fig. 2(b), the minimum and maximum transmission values are about 0.2 and 0.5, respectively. In practice, it is highly desirable to have considerable contrast between the transmission peak and dip. Considering that a single bright particle is not enough to block the guided wave, another bright particle may be added at the right-top corner of the dark particle to further reduce the minimum transmission. A cell is formed by one dark particle and two bright particles. Moreover, the idea of Fabry-Perot (FP) resonance

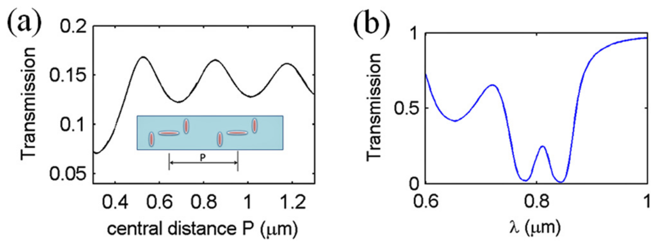

FIG. 3. (Color online) (a) Transmission variation at wavelength 0.8 μm as central distance P between two cells changes. (b) Transmission spectrum corresponding to $P = 0.53$ μm at which the first maximum transmission peak appears in (a).

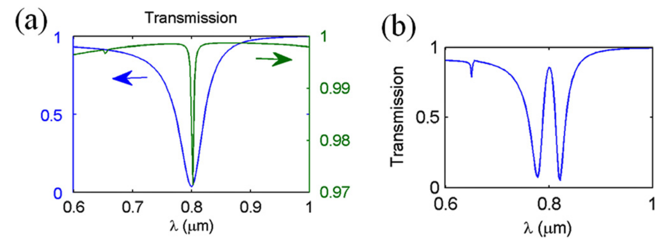

FIG. 4. (Color online) Transmission spectrum when the damping factor of the silver is reduced to $\Gamma_2 = \Gamma/10$. Except the damping factor of the silver, the other parameters used in (a) and (b) are the same as those in Figs. 1 and 2, respectively.

between two cells may be utilized to further increase the transmission peak/dip ratio.[6] The improved configuration is shown in the inset of Fig. 3(a). The waveguide transmission at a fixed wavelength will vary when the central distance (P) between the two cells changes. The transmission variation shown in Fig. 3(a) exhibits a typical FP resonance character at wavelength 0.8 μm. The first transmission peak appears at $P = 0.53$ μm. When P is fixed at 0.53 μm, Fig. 3(b) shows the corresponding transmission spectrum. Due to the presence of two resonant cells, the transmission at the dips is almost zero. Eventually, significant improvement of the transmission contrast is obtained. In Fig. 3(b), it is noticed that the transmission peak wavelength shifts slightly to 0.81 μm. In fact, this wavelength shift arises from the presence of the second bright particle inside one single cell, rather than the FP interaction of the two neighbouring cells. The transmission spectrum of a single cell (not shown here) has exhibited the same transmission-peak-wavelength shift.

Finally, the influence of metal's Joule loss on the proposed EIT scheme is investigated. For illustration, the damping factor of silver is assumed to be ten times smaller then that used in the above calculation, while the other parameters are exactly the same as used in Fig. 1(b). Compared with Fig. 1(b), the results in Fig. 4(a) show that the Joule loss has a great impact on the quality factor of the dark particle. A small damping factor will greatly enhance the quality factor and reduce the resonant line width. On the other hand, the quality factor of the bright resonator is more or less independent on the damping factor. In other words, the radiative loss dominates over the Joule loss for the bright dipole resonator, but the Joule loss dominates over the radiative loss for the dark quadrupole resonator. The updated EIT spectrum for the same structure in Fig. 2(a) with a smaller damping factor of silver is shown in Fig. 4(b). It is clear that the resonance of the dark particle is significantly enhanced, and the transmission contrast is fairly large. Thus, it is hoped that a low-loss plasmonic material can achieve a satisfying EIT effect for practical use. Dissipation compensation with gain material may provide a possible way to improve the EIT performance.[14,15]

In conclusion, we have proposed coupled plasmonic resonators inside a slab waveguide for realizing EIT-like transmission spectrum at the visible frequencies. A basic configuration and an improved configuration have been investigated. The influence of the metallic damping factor on the EIT performance has also been investigated. The present design idea will find its application in ultra-compact micro- or nano-scale optical circuits, slow light, and sensing areas.[13,16]

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[1]S. E. Harris, Phys. Today **50**(7), 36 (1997).
[2]L. V. Hau, S. E. Harris, Z. Dutton, and C. H. Behroozi, Nature **397**, 594 (1999).
[3]Q. Xu, S. Sandhu, M. L. Povinelli, J. Shakya, S. Fan, and M. Lipson, Phys. Rev. Lett. **96**, 123901 (2006).
[4]S. Zhang, D. A. Genov, Y. Wang, M. Liu, and X. Zhang, Phys. Rev. Lett. **101**, 047401 (2008).
[5]N. Papasimakis, V. A. Fedotov, N. I. Zheludev, and S. L. Prosvirnin, Phys. Rev. Lett. **101**, 253903 (2008).
[6]R. D. Kekatpure, E. S. Barnard, W. Cai, and M. L. Brongersma, Phys. Rev. Lett. **104**, 243902 (2010).
[7]S. A. Maier, *Plasmonics: Fundamentals and Applications* (Springer, New York, 2007).
[8]M. I. Tribelsky and B. S. Luk'yanchuk, Phys. Rev. Lett. **97**, 263902 (2006).
[9]C. F. Bohren and D. R. Huffman, *Absorption and Scattering of Light by Small Particles* (Wiley, New York, 1998).
[10]M. Barth, S. Schietinger, S. Fischer, J. Becker, N. Nüsse, T. Aichele, B. Löchel, C. Sönnichsen, and O. Benson, Nano Lett. **10**, 891 (2010).
[11]R. Ameling and H. Giessen, Nano Lett. **10**, 4394 (2010).
[12]L. Chen, G. P. Wang, Q. Gan, and F. J. Bartoli, Phys. Rev. B **80**, 161106 (2009).
[13]B. Luk'yanchuk, N. I. Zheludev, S. A. Maier, N. J. Halas, P. Nordlander, H. Giessen, and C. T. Chong, Nat. Mater. **9**(9), 707 (2010).
[14]A. Fang, T. Koschny, M. Wegener, and C. M. Soukoulis, Phys. Rev. B **79**(24), 241104 (2009).
[15]J. Grandidier, G. C. Francs, S. Massenot, A. Bouhelier, L. Markey, J.-C. Weeber, C. Finot, and A. Dereux, Nano Lett. **9**(8), 2935 (2009).
[16]N. Papasimakis and N. I. Zheludev, Opt. Photon. News **20**(10), 22 (2009).