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Enhanced sensing performance by the plasmonic analog of electromagnetically induced transparency in active metamaterials

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The gain-assisted plasmonic analog of electromagnetically induced transparency (EIT) in a metallic metamaterial is investigated for the purpose to enhance the sensing performance of the EIT-like plasmonic structure. The structure is composed of three bars in one unit, two of which are parallel to each other (dark quadrupolar element) but perpendicular to the third bar (bright dipolar element). The results show that, in addition to the high sensitivity to the refractive-index fluctuation of the surrounding medium, the figure of merit for such active EIT-like metamaterials can be greatly enhanced, which is attributed to the amplified narrow transparency peak. © 2010 American Institute of Physics. [doi:10.1063/1.3488020]

Plasmonically induced transparency, also called plasmonic analog of the electromagnetically induced transparency (EIT),1–4 is an interesting phenomenon in metamaterials wherein bright-mode energy is transformed into a dark mode through plasmon coupling between the adjacent resonant elements. This phenomenon results in a narrow transmission peak with a high quality factor within the originally broad stop band (bright mode) of the transmission spectrum. Here, the bright mode indicates a far-field excitable resonance with radiative losses, such as the dipolar resonance of a single-rod array. The dark mode, on the contrary, cannot be excited by a far-field source and does not radiate into outer environment (high quality factor). For example, the quadrupolar resonance of a rod-pairing array is “dark” to incident waves when the polarized \( H \) field is parallel to the rod-pair plane. Such a metamaterial version with EIT feature is considered as a plasmonic analog of the EIT phenomenon in atomic physics. From the quantum point of view,5,6 it happens when the excitation pathway \( |0\rangle \rightarrow |1\rangle \) interferes destructively with another pathway \( |0\rangle \rightarrow |2\rangle \rightarrow |1\rangle \), where \( |0\rangle \rightarrow |1\rangle \) means a dipole-allowed transition (bright mode) from the ground state \( |0\rangle \) to the excitation state \( |1\rangle \), whereas direct transition \( |0\rangle \rightarrow |2\rangle \) is forbidden (dark mode). Nevertheless, the excitation state \( |2\rangle \) can be accessed through plasmon-coupling transition \( |1\rangle \rightarrow |2\rangle \).

Generally, although it is similar regarding the capability of opening a narrow transparency window within a transmission stop band, the plasmonically induced transparency differs from a native EIT in atomic system for several aspects. First, it happens through a high efficiency of plasmon coupling between the bright and dark modes, rather than by an external beam to control the EIT window. Second, the EIT-like feature occurs only when the dark mode is at the identical resonant frequency range with the bright mode. Third, the EIT-like phenomenon can only suppress the radiative damping by transferring the energy from the bright (radiative) mode into the dark (subradiant) mode. In other words, the intrinsic Ohmic loss inside the metal can never be compensated in these EIT-like structures. Consequently, although EIT-like metamaterials integrate the dual advantages of EIT-like narrow window (dark-mode excitation) and surface plasmon resonance (strong field confinement) for sensor applications,7,8 low transmittance due to the intrinsic Ohmic loss in EIT-like metamaterials needs to be improved for a better sensing efficiency. Recently, nonlinear active media such as quantum dots have been used to compensate for the Ohmic loss in plasmonic structures.9 In particular, stimulated emission of radiation can amplify the surface plasmon resonance considerably in such active plasmonic systems,10 inspiring proposals on interesting nonlinear optical devices, such as nanolaser or lasing spaser.11,12 In this work, we demonstrate that the resonance amplification in active plasmonic metamaterials can be applied to EIT-like metamaterial sensors for a great enhancement of the sensing capability.

For the EIT-like phenomenon in metallic metamaterials, the bright element is either a single bar or a split ring resonator, if only it is directly excitable by the incident waves and meanwhile has a broader linewidth than does the dark element, usually comprising split ring resonator,13–16 pairing bars,2,4,17 and double rings.18,19 In this work, we take the previously studied three-bar configuration2–4 to investigate the active plasmonic analog of EIT in order to enhance the performance of sensing the refractive-index fluctuation of the surrounding medium.

Figure 1 shows a schematic illustration of the unit cell of the metallic metamaterial with structural parameters as follows: \( a = 460 \text{ nm}, b = 80 \text{ nm}, t = 40 \text{ nm}, g = 300 \text{ nm}, h = 110 \text{ nm}, \text{ and } l = 260 \text{ nm}. \) The periodicity in both \( x \) and \( y \) direction is \( p_x = p_y = 700 \text{ nm}, \) while only single unit layer is considered in the \( z \) direction. Under the incident polarization situation in Fig. 1(a), the dipolar oscillation is a bright mode in the perpendicularly stacked bar, whereas the quadrupolar mode is a dark mode inherent to the double parallel bars.
which can only be excited through plasmon coupling by introducing the symmetry-broken shift $s$ [Fig. 1(b)]. A full-wave finite element method is used for the simulation,\textsuperscript{12,18} which automatically takes account of the diffraction effect by solving the Maxwell’s Equations with given material property, structure, and boundary conditions. The perfect electric and magnetic boundaries are used in compliance with the incident configuration in Fig. 1(a). The metal is silver with Drude dispersion ($\omega_0=1.37 \times 10^{16}$ s$^{-1}$ and $\gamma=8.5 \times 10^{13}$ s$^{-1}$),\textsuperscript{20} for which the substrate is glass with an index of refraction of 1.55. The metallic structure is embedded in a host material of polymethyl methacrylate (index of refraction 1.49), in which the gain medium (for example, PbS semiconductor quantum dots) is sparsely doped. A frequency-dependent complex permittivity is used to characterize the active property with gain coefficient $\alpha=(2\pi/\lambda)\text{Im}(\varepsilon'+i\varepsilon'')$, where $\varepsilon'$ and $\varepsilon''$ are the real and imaginary parts of the permittivity for the active system, respectively.\textsuperscript{12,21}

To evaluate the EIT-like response of this structure in the absence of gain, the transmittance spectra for $\alpha=0$ cm$^{-1}$ at different asymmetry shifts $s$ are presented in Fig. 2. It is found that more asymmetry degree by increasing $s$ results in broader EIT range as well as larger transmittance, corresponding to the so-called Autler–Townes doublet in atomic systems.\textsuperscript{22,23} This broadening, although with enough transmission intensity, is not preferable for sensing performance because of the degenerated figure of merit (FOM).\textsuperscript{24–27} On the other hand, a smaller asymmetry shift $s$ results in a more pronounced narrow EIT feature, but unpleasantly the transmittance is suppressed.\textsuperscript{3} Therefore, a narrow transmission peak with high transmittance for sensing purpose could not be managed simultaneously in a passive EIT-like metamaterial, unless an active medium will be introduced to compensate for the intrinsic Ohmic loss.\textsuperscript{2}

Figure 3 shows the gain-assisted transmittance transition of the EIT-like window at $s=20$ nm. It is found that the transparency peak enhances its transmittance dramatically, corresponding to the formula $\text{FOM}=m(\text{RIU}^{-1})/\text{FWHM}(\text{nm})$, the sensi-
surrounding medium, even for a small fluctuation in the refractive index of the transparency window exhibits a distinct resonance shift with respect to a gain coefficient, calculated at the refractive index of the surrounding medium in dependence on the gain coefficient, calculated at the refractive index of $n = 1$. The red curve provides a Lorentian fitting.

![Figure 4](image)

**FIG. 4.** (Color online) The sensing performance for the active EIT-like transparency window. (a) The resonance shift in the EIT-like peak on the refractive-index fluctuation of surrounding medium, calculated at gain coefficient $\alpha = 850$ cm$^{-1}$. (b) The FOM of the active EIT-like transparency peak in dependence on the gain coefficient, calculated at the refractive index of $n = 1$. The red curve shows a high sensitivity about 680 nm/RIU. Therefore, it offers an excellent potential for ultra-high resolution situations, such as bio-imaging and gas detection. The wavelength shift in the transparency peak per refractive-index unit shows a high sensitivity about 680 nm/RIU. In addition, the sensing performance in terms of FOM, by taking into account the sharpness of a transmission peak, offers another advantage due to the assistance of the gain medium. As is shown in Fig. 4(b), the gain dependence of the FOM actually indicates a great improvement in the sensitivity performance, from which the gain-assisted FOM can reach a maximum value as large as 400 when a suitable gain coefficient is introduced. However, it should be noticed that the FOM could decrease substantially when the refractive index of the surrounding medium changes widely so that it may result in a shifted EIT-like transparency frequency far from its original gain value of an active medium, which is frequency dependent and generally has a Gaussian distribution. In this sense, the gain-assisted FOM also depends, indirectly, on the refractive index of the surrounding medium. Therefore, an in situ control of the gain coefficient should be desired to keep the enhanced FOM as is throughout a wide refractive-index change of the surrounding medium.

In summary, a sensing scheme that incorporates the active mechanism in a plasmonic metamaterial and the narrow transparency feature of the EIT phenomenon is proposed to enhance the sensing performance. Three distinguishing characteristics can be concluded. First, the EIT-like resonances, originating from the dark-mode excitation by plasmon coupling, has a great sensitivity as much as 680 nm/RIU. Second, the gain-assisted FOM in the EIT-like plasmonic metamaterial can reach a value around 400, demonstrating an ultrahigh enhancement of the sensing performance. Third, a reliable gain coefficient in the order of hundred inverse centimeter is sufficient for the greatly enhanced sensing performance, not only because the underlying EIT mechanism is lossless, but also because the unique active mechanism in plasmonic metamaterials.

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