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Plasmon induced transparency in a surface plasmon polariton waveguide with a comb line slot and rectangle cavity

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The phenomenon of electromagnetically induced transparency (EIT) is demonstrated in a surface plasmon polariton waveguide at infrared frequencies. The comb line slot and rectangle cavity are placed inside one of the metallic claddings, and their coupling intensities among them are utilized to obtain bright and dark states. The destructive interference between the bright and dark states leads to an EIT-like transmission spectrum of the waveguide. The induced transparency peak can be manipulated by adjusting the coupling distance between the bright and dark states. Finally, the influence of Joule loss on the EIT-like effect is investigated. It is found that the EIT-like transmission contrast is sensitive to the variation in the metallic damping factor. *© 2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4883647]

Electromagnetically induced transparency (EIT) is a quantum interference effect that reduces light absorption over a narrow spectral region in a coherently driven atomic system.[1–3] Since the sharp resonance and steep dispersion could achieve in EIT, these systems show remarkable potential for slow light and optical data storage.[4] 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. Examples include cut wires,[5] split-ring-resonators (SRRs),[6–9] waveguide system,[10,11] and other multi-layer structures.[12,13] Nowadays, the use of novel techniques to fabricate microstructures to control light has been exciting developments in optical physics.[14] Electromagnetic waves trapped on metal-dielectric interfaces and coupled to propagating free electron oscillations in metals, known as surface plasmon polaritons (SPP), are regarded as the most promising way for realization of highly integrated optical circuits due to significant overcoming of classical diffraction and manipulation of light in a nanoscale domain.[15–17] As an important plasmonic device, SPP waveguides attract more and more attention due to their deep-subwavelength confinement of light.[18–20] SPP waveguides are regarded as one of the most promising candidates for the nanoscale manipulation and transmission of light.[21] SPP waveguide-resonator systems offer a pathway for the realization of photonic functionality in metallic nanostructures.

Motivated by the above fundamental studies, in this Letter, we would like to achieve an EIT-like phenomenon inside a SPP waveguide configuration with a comb line slot and rectangle cavity at infrared frequencies. Our results reveal that the EIT-like phenomenon in our designed system can be achieved based on the dark-bright coupling mechanisms and the transparency peak can be tuned by adjusting the coupling distance between dark and bright states. In addition, we also investigate the influence of Joule loss on the EIT effect in our model.

The SPP waveguide system considered in this Letter is sketched in Fig. 1(a), and it is formed by using air as the core (thickness $w = 50$ nm). The metallic claddings of the SPP waveguide are loss silver, which permittivity can be described by Drude model, $\boxed{\epsilon_{Ag}(\omega) = 1 - \omega_p^2/[\omega(\omega + i\Gamma)]}$, 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. Based on the theory in Ref. 22, if we want to achieve EIT-like phenomenon, we must to construct light and dark state structure in our SPP waveguide system. In our study, the comb line slot and rectangle cavity are considered as EIT elements and arranged on one of the metallic claddings of the SPP waveguide (see Fig. 1(a)) and the finite-element method is used for numerical simulation. The comb line slot ($g = 580$ nm, $b = 20$ nm) which is filled with air is connected to the air core at one end, as shown in Fig. 1(a). As a branch of the core, the comb line slot can be excited directly by the input wave. Therefore, the comb line slot can be considered as the bright resonator. Rectangle cavity which is filled by silicon ($\epsilon = 12.25$) with $h = 55$ nm width, $s = 100$ nm length is side coupled with the SPP waveguide (see Fig. 1(a)). The distance between the rectangle cavity and the air core is denoted by c. When c is very small, the rectangle cavity could be excited by the transverse-magnetic (TM) wave due to the near-field coupling. The transmission spectra of the SPP waveguide side coupled with single rectangle cavity for different c are shown in Fig. 1(b). The different transmission dips in the Fig. 1(b) indicate that rectangle cavity has different resonant frequencies, when c takes different values. It is also found that the coupling strength decreases rapidly with the increase in c. For example, when $c = 10$ nm, the rectangle cavity has a resonant mode at 286 THz, however, when $c = 150$ nm, although this value is still smaller than the wavelength, no resonance appears in the spectra, as shown in Fig. 1(b). It means that direct coupling between rectangle cavity and SPP waveguide is negligible for $c = 150$ nm. In this sense, the rectangle cavity could be considered as a dark resonator in the EIT

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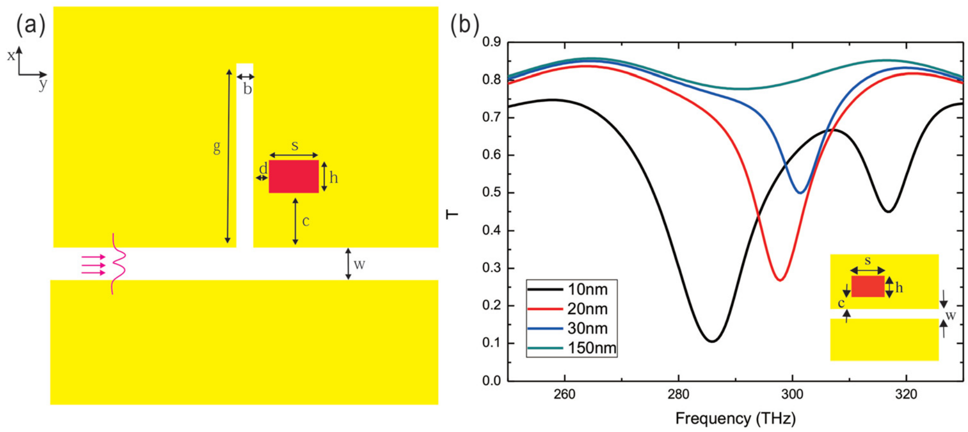

FIG. 1. (a) Schematic diagram of the nanoscale plasmonic resonator system. (b) The transmission spectra of the SPP waveguide side coupled with single rectangle cavity when c has different values.

elements. Moreover, the dark state in this work is achieved in a straightforward way.

Based on the above analysis, the geometric parameters d and c of our model (see Fig. 1(a)) are set as 10 nm and 150 nm. There are three reasons for this arrangement. First, when c = 150 nm, the TM wave which is incident from left can couple with comb line slot directly, but cannot couple with the rectangle cavity. Doing so can ensure that the bright and dark resonator can exist in this system simultaneously. Moreover, when d = 10 nm, the bright and dark resonator approach each other, near-field coupling between them will take place. Third, such arrangement is chosen to guarantee that the resonance frequency of dark resonance coincides with that of the bright resonance. Meanwhile, the bright resonator exhibits strong broad-band resonance excitation, while the dark resonator exhibits weak narrow-band resonance excitation. Fig. 2(a) has a good exhibition for it. Thus, the EIT-like transmission can easily be demonstrated in our structure, as shown in Fig. 2(b). Fig. 2(c) shows the electric amplitude distributions corresponding to the three characteristic frequencies represented by A, B, and C in Fig. 2(b). The resonance characteristics of the bright and dark states can be clearly distinguished. At the frequencies f_A and f_C, the bright resonator is effectively excited. However, the excitation of the dark resonator is extremely weak. This is due to the weak electric field strength in the comb line slot around c = 150 nm. In this case, most of the incident optical wave energy is strongly reflected by the bright resonator and leaks out into the outside space. Therefore, the transmission of the waveguide at frequencies f_A and f_C is low, as shown in Fig. 2(b). At frequency f_B, due to the strong electric field strength in the comb line slot around c = 150 nm, the coupling effect

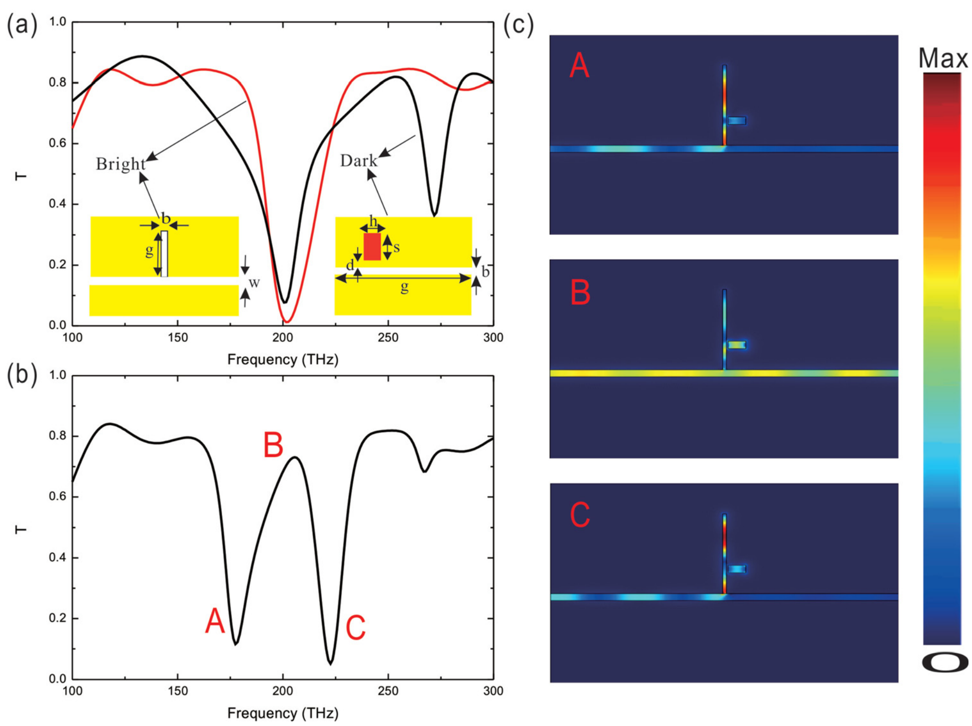

FIG. 2. (a) The transmission spectrum of bright and dark state, respectively. (b) EIT transmission spectrum of the nanoscale plasmonic resonator system. (c) Distributions of electric amplitude corresponding to the three frequency values represented by A, B, and C, in (b).

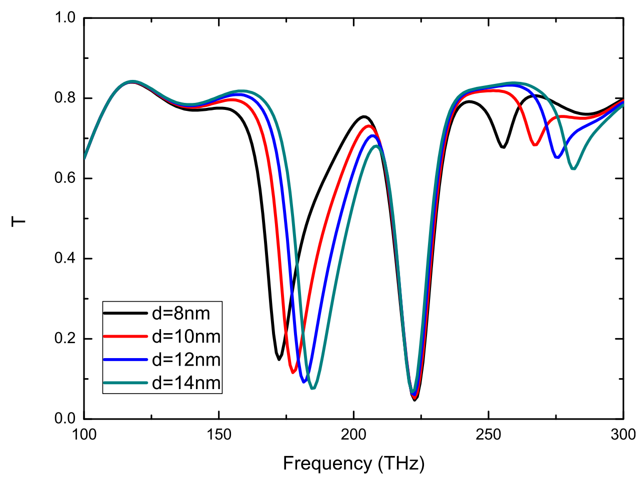

FIG. 3. Transmission spectra at different coupling distance between the bright and dark resonator.

between the bright and dark resonator will lead to strong resonance of the dark resonator. The strong excitation of the dark resonator can suppress the oscillation of the bright resonator in a destructive way. This means that the interaction between bright and dark resonator results in a weak excitation of bright resonator and a strong excitation of dark resonator (see the middle panel of Fig. 2(c)). Thus, a transmission peak occurs at the frequency f_B (see Fig. 2(b)).

It is widely recognized that the EIT-like phenomenon can be regarded as a special case of Fano resonance.[23] The coupling strength between bright and dark states will play an important role for the peak value and line width of the EIT spectrum. Fig. 3 shows transmission spectra at different coupling distance d. It is found that the induced transparency peak and transmission spectrum width decrease with the increase in coupling distance. The reason for this phenomenon is that the increase in coupling distance can lead to the decrease of the coupling strength. Therefore, the induced transparency peak can be manipulated by adjusting the coupling distance between the bright and dark states.

It is known that the metal's Joule loss will have an important impact on the transmission of the electromagnetic wave. Thus, it is necessary for us to investigate the influence of metal's Joule on the properties of EIT scheme which is generated by our model. For illustration, the damping factor of sliver is assumed to be ten times smaller than that used in the above calculation, while the other parameters are exactly the same as used in Fig. 1(a). Compared with Fig. 2(b), the results in Fig. 4(a) show that the Joule loss has a slight impact on the quality factor of the bright and dark resonator. However, the Joule loss has a great impact on the resonance strength of the bright and dark resonator, i.e., the transmission values are zero at the resonance point of bright and dark resonator. In other words, the reflect loss dominates over the Joule loss for the quality factor of the bright and dark resonator, but the Joule loss has a great impact on the coupling strength between the bright and dark resonator. The updated EIT spectrum for the same structure in Fig. 1(a) with a smaller damping factor of sliver is shown in Fig. 4(b). It is clear that the transmission contrast is fairly large. Thus, we hope that a low-loss plasmonic material can achieve a satisfying EIT effect for practical use. In recent years, researchers have found that when $\sigma_{g,i} > 0$ (imaginary part of the graphene's complex conductivity), a graphene layer effectively behaves as a very thin "metal" layer capable of supporting a TM electromagnetic SPP surface wave in the range of the visible and infrared.[24] Comparing with noble metals, the graphene has many excellent properties, such as low-loss and controllable conductivity.[24–27] It is a suitable alternative material to noble metal. The researchers also found that the wave band of EIT could be tuned freely in graphene-based artificial structure.[28] Thus, these findings provide us a possible way to improve the EIT performance in our future research work.

In summary, the EIT-like effect has been investigated numerically in the nanoscale plasmonic resonator system which consists of a comb line slot, rectangle cavity, and SPP waveguide. The induced transparency peak can be manipulated by adjusting the coupling distance between the bright and dark resonator. The influence of the metallic damping factor on the EIT performance has also been investigated. It is found that the EIT-like transmission contrast is strongly sensitive to the variation in the metallic damping factor. The finite-element method results can be accurately analyzed by the theoretical model. The present design idea will find its

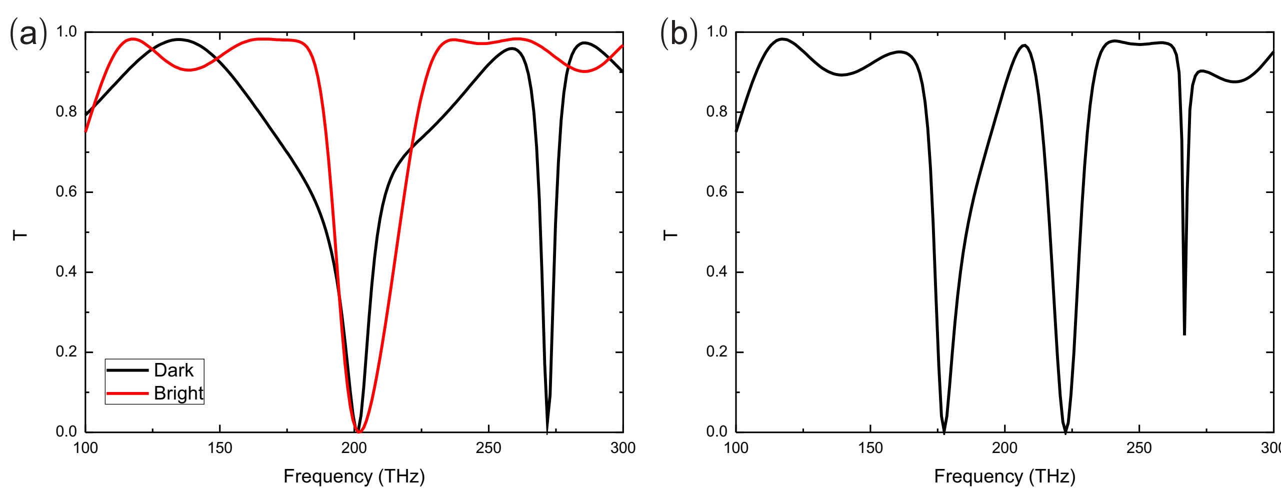

FIG. 4. Transmission spectrum when the damping factor of the silver is reduced to $\Gamma/10$. Except the damping factor of the silver, the other parameters used in (a) and (b) are the same as those in Figs. 1 and 2, respectively.

application in nanoscale optical switching, nanolaser, and slow-light device in highly integrated optical circuits.

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