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# New Approach of Plasmonically Induced Reflectance in a Planar Metamaterial for Plasmonic Sensing Applications

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**Abstract** We theoretically demonstrate and investigate plasmonically induced reflectance (PIR) in a new planar metamaterial with two completely different approaches. Here, we not only show that broken symmetry is a general strategy to create electromagnetically induced reflectance (EIR)-like effect but also demonstrate that the nanoplasmonic EIR can be realized even without broken symmetry via the excitation of the higher-order plasmonic modes in the same designed planar metamaterial. In nanophotonics, plasmonic structures enable large field strengths within small mode volumes. Therefore, combining EIR with nanoplasmonics would open up the way toward ultracompact sensors with extremely high sensitivity. In the second approach of creating the PIR of our proposed nanostructure, the restrictions on size are partially relaxed, making fabrication much easier. Their interactions and coupling between plasmonic modes are investigated in detail by analyzing field distributions and spectral responses. Also, we show that the PIR frequency position depended very sensitively on the dielectric surrounding. Furthermore, the narrow and fully modulated PIR features due to the extraordinary reduction of damping may serve for designing novel devices in the field of chemical and biomedical sensing.

**Keywords** Nano-plasmonic · Electromagnetically induced reflectance (EIR) · Planar metamaterials · Plasmonic sensing applications

## Introduction

Electromagnetically induced reflectance (EIR) refers to the formation of a reflection window inside the absorption band of an atomic system. Optical metamaterials emerge as a new platform for the realization of the EIR that is sometimes referred to as plasmonically induced reflectance (PIR) [1]. Despite electromagnetically induced transparency (EIT) is a quantum mechanical effect, it is possible to observe classical EIT-like effects in metamaterials [2–4] and plasmonic structures [5–12]. Even thought, EIT results from a quantum interference in atomic systems while its classical version has been investigated in metamaterials theoretically and experimentally based on arrays of metallic nanoparticles [13] and optical antennas [5, 6, 14, 15]. The coupling of the bright and dark plasmonic modes can lead to destructive interference of the excitation pathways giving rise to a sharp peak of nearly perfect reflection within a broad reflectance dip. One of the most exciting effect is the realization of the classical analog of EIT in plasmonic systems [5, 6, 16]. It is worthy to note that metamaterials with EIR-like effects can have low-loss property and sensing ability for refractive-index changes of the surrounding medium. Especially EIT has a great benefit in nanophotonics as well as quantum information and optical switching devices [17]. Also, the application of optical dipole antennas is of great interest with the features of subwavelength, since the half-wavelength scaling breaks down when the localized surface plasmon polaritons (SPPs) play a role in the electromagnetic response [18]. In localized surface plasmon resonance (LSPR) sensor applications, the sensing medium easily fills the voids, therefore facilitating the detection of refractive index changes [1]. Our design has a great potential for near-infrared LSPR sensing applications, a benefit substantiated by the narrow linewidth and high modulation depths

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of the EIR-like features in both symmetric and asymmetric structures.

In our previous study of the PIT [19], the unit cell of the metamaterial was made of the two metal antennas, optical dipole, and quadruple antenna. The former consisted of an H-shape silver strip and the latter was composed of a pair of metal strips. In that work, we have shown PIT effect in two different cases. In this work, we have designed and investigated a planar metamaterial structure made of a silver thin-film layer and two antennas. In fact, our structure composed of cut-out antennas in a metal thin-film (see Fig. 1). The unit cell consisting of an H-shape cut-out in a metal thin-film as a bright mode (dipole antenna) and cut-out strips pair used as a dark mode that filled with dielectric. In fact, in the PIR similar to EIT-like effect, a plasmonic mode can be either superradiant (radiative or bright mode) or subradiant (dark mode) depending on how strong an incident light from free space can be coupled into the plasmonic mode [5, 6]. The bright plasmonic mode has a large scattering cross section and a low-quality factor due to the radiation coupling, whereas the dark plasmonic mode has a significantly larger quality factor, which is limited only by the loss of the metal. When these slot antennas are placed closely to each other in a planar thin film of silver, the dark plasmonic mode can be coupled to the external light by the bright mode. In order to generate PIR effect, coherently coupled bright and dark modes are introduced. A slot dipole antenna (cut-out H-shape), which is strongly coupled to the light, supports the spectrally broad bright mode; and also a slot quadruple antenna (cut-out strips pair), which is non-radiative in nature, supports the spectrally narrow dark mode. In fact, the quadruple antenna has a much narrower linewidth compared to that of the dipole antenna due to the suppression of radiation damping. As a result, destructive interference between two possible excitation pathways, namely the direct excitation of the slot dipole antenna by the external light and the excitation by coupling with the slot quadruple antenna, leads to PIR effect. All geometrical parameters are defined in Fig. 1a. The permittivity of silver was modeled using the Drude formula: $\epsilon_m = 1 - \frac{\omega_p^2}{\omega(\omega+i\nu_c)}$ [20, 21], where the electric plasma frequency $\omega_p$ and the collision frequency $\nu_c$ are presented in Table 1. The substrate is glass with an index of refraction $n = 1.55$, and two slot antennas were made of a dielectric with index of refraction $n = 2.15$. Consider a polarization of incident wave with electric field along the X-direction and magnetic field along the Y-direction. In fact, in accordance to Babinet's principle, we have rotated the whole of the previous structure 90° in comparison with PIT structure in our previous work [19]. In accordance to Babinet's principle, instead of enhanced transmission, a sharp reflectance peak within the broad spectral profile is established. This phenomenon was called EIR-like effect [1]. This phenomena in a planar metamaterial is highly desirable for sensing applications [22–24]

For the study of optical properties of the proposed planar metamaterial, we have used the scattering matrix theory [25, 26] and FDTD method [27] for numerical simulation. CST Microwave Studio, a computer simulation technology was used for this propose.

This paper is organized as follows. In "Plasmonically Induced Reflectance in a Planar Metamaterial Structure with Broken Symmetry" section, we investigate the coupling between incident light and plasmonic modes (dark and bright modes) shown in Fig. 2; also, we perform a detailed study of the PIR effect in suggested structure with broken symmetry. Moreover, we illustrate the electric field distribution for better understanding of underlying physics. In "Plasmonically Induced Reflectance in a Symmetric H-II Cut-Out Structure" section, we demonstrate that the PIR effect can be realized even in symmetric structure in a planar metamaterial. Finally, in "Comparison of the Effect of Different Metals and Dielectrics on Spectral Response at PIR Frequency" section, we investigate and study the

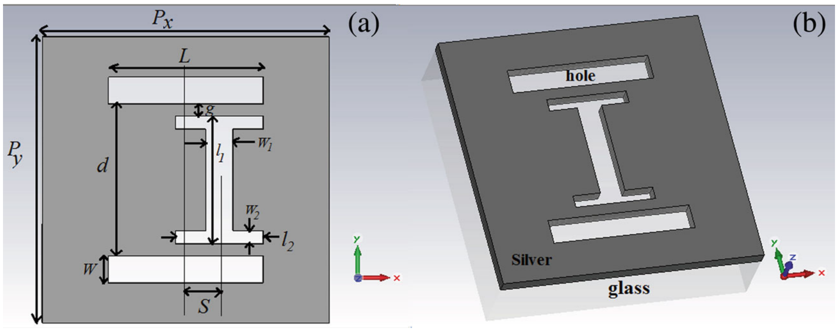


**Fig. 1** **a** Two-dimensional view of the unit cell of the planar plasmonic MM (referred to as H-II cut-out structure) proposed in this study in an asymmetric case ($S$ = 100 nm). The geometric parameters are $L$ = 460 nm, $d$ = 430 nm, $l_1$ = 360 nm, $l_2$ = 260 nm, $W$ = 80 nm, $w_1$ = 80 nm, $w_2$ = 40 nm, $g$ = 35 nm, $t$ = 40 nm, S: from $S = 0$ to $S = 190$ nm. The periodicity in both x- and y-direction is $P_x = P_y = 850$ nm. Incident plane waves are irradiated along the z-direction, and its electric component, **E**, is parallel to the x-direction and magnetic field, **H** is parallel to y-direction. **b** Three-dimensional view of a symmetric structure ($S = 0$ nm)

**Table 1** Plasma and collision frequency of different metals [30]

| Metals | Plasma frequency ($\omega_p \times 10^{15} S^{-1}$) | Collision frequency ($\nu_c \times 10^{15} S^{-1}$) |
|---|---|---|
| Silver | 14.0 | 0.032 |
| Gold | 13.8 | 0.11 |
| Copper | 13.4 | 0.14 |
| Aluminum | 22.9 | 0.92 |

effect on dielectric surrounding near silver nanoparticles; and also, we compare the effect of different metals on spectral response at PIR frequency. Furthermore, we show the electric and magnetic field distributions in a symmetric structure at PIR frequency. Main results are summarized in the last section.

## Plasmonically Induced Reflectance in a Planar Metamaterial Structure with Broken Symmetry

As mentioned in the previous section, our proposed nanostructure composed of slot antennas in a homogeneous silver thin film (see Fig. 1). At first, we have studied the coupling of incident light with plasmonic modes (Fig. 2). Also, in order to better understand the underlying physics, the calculated z-component of electric field distributions at the PIR frequency in all cases and the excited surface currents at three different frequencies near PIR are illustrated in Figs. 3 and 4.

As it is clear from Fig. 2, when the silver thin-film is exposed to normal incident light, the reflection is nearly close to 1 due to no coupling with the external field; and also the z-component of electric field for this case (Fig. 3a) shows there is no coupling between the silver thin-film and the normal incident light. Then, we have stimulated three more cases. The first one is when only the dark mode is exposed to the normal incident light, there is no strong coupling with the external field (as clearly shown in Figs. 2 and 3b). In fact, in order to use an incident polarized light in our structure, when we have normal incidence, the resonance fully originates from the electric component of the light; and the reflection spectrum of the dark plasmonic mode (quadruple antenna) still shows that is inactive at normal incidence, where the reflection spectral response is nearly close to 1 due to no strong coupling with the external field like the case of silver thin-film. As obviously can be seen from Fig. 2, with this important feature, this plasmonic modes are called “dark or non-radiative mode.”

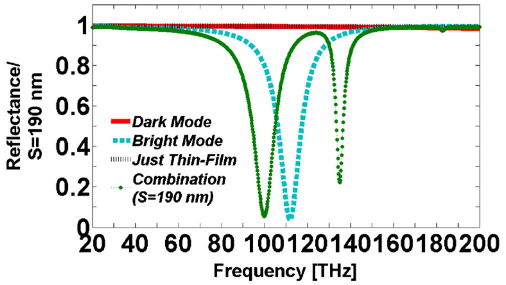
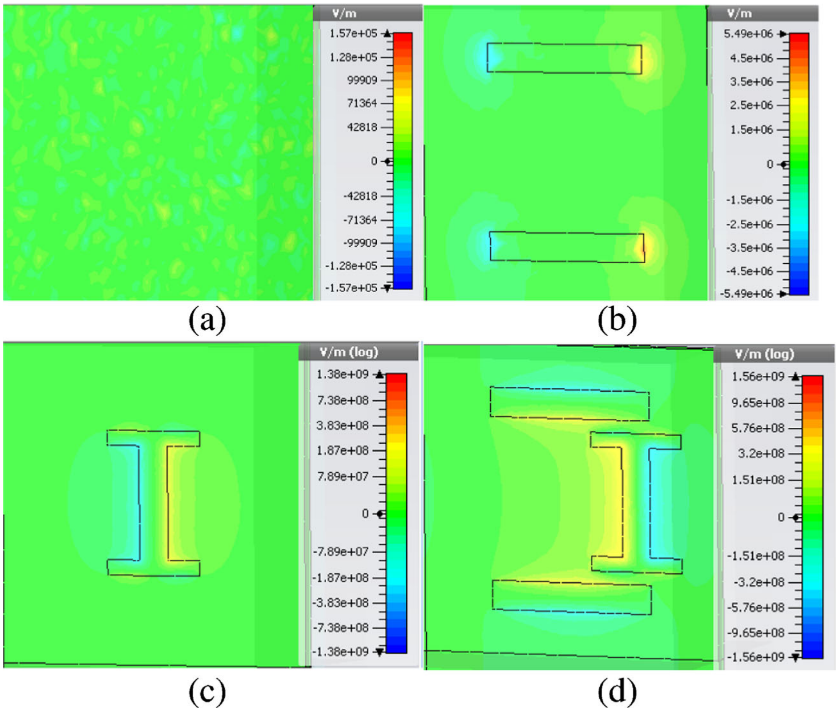


**Fig. 2** *Red-line*, *blue-dashed*, *black-dotted*, and *green-fully-circles curves* represent the simulated results of reflectance spectra of the dark, bright plasmonic mode, silver thin-film, and combination of dark and bright plasmonic modes with each other for the case of asymmetric (i.e., $S$ = 190 nm) proposed planar metamaterial structure respectively

Also as can be seen from electric field distribution for dark plasmonic mode (Fig. 3b), there is a week coupling between the two strips pair and the normal incident light. The z-component of electric field distribution for the dark mode (Fig. 3b) shows the dark mode cannot directly and strongly couple to the normal incident light. But when the bright plasmonic mode is exposed to the normal incident light, there is a resonance in reflection spectra that shows it (slot H-shape dipole antenna) directly and strongly coupled to incident light from free space. This is the main reason, it is called “bright mode.” As clearly can be seen from Fig. 3c, the electric distribution for the bright mode is strong but the electric moments have the same magnitude in opposite directions; thus, they cancel each other out and there is no net electric moment in bright plasmonic mode. Hence, we cannot see any PIR effect in this case. However, when the dark and bright plasmonic modes are combined with each other in the metamaterial, the plasmonic EIR (PIR) comes out because the dark mode is activated through the near-field interaction in the case of broken symmetry ($S$ = 190 nm) and it could couple with the external field by the bright mode. As it is clear in Fig. 3d, electric moments around the bright plasmonic mode are not equal and one side has a higher electric moment than the other side. Therefore, they cannot cancel each other out (although they have different directions with respect to each other). As a result, a net electric moment exists which induces circular currents in the dark plasmonic mode which results in the excitation of the dark mode and finally causes to create PIR effect in an asymmetric case ($S$ = 190 nm).

Figure 4 shows the excited surface currents at the reflectance peak $\omega_0$ and two other frequencies near the PIR $\omega_0 \pm \Delta\omega$. As it is clear in Fig. 4, the excited surface currents exhibit different oscillating behavior at three characteristic frequencies. The bright plasmonic mode is different from the dark one under the following condition; the bright mode should be stable under the external excitations, which means it can be directly excited by the incident field [28]. As shown in Fig. 4c, the slot H-shape antenna exhibits circular surface currents from left to right at $\omega_0 - \Delta\omega$ and stay circular from



(a) (b)

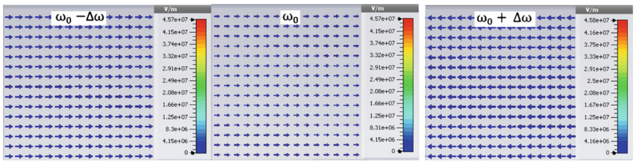
(c) (d)

**Fig. 3** Z-component of electric field distributions in the PIR frequency for the case of **a** thin-film, **b** dark plasmonic mode, **c** bright plasmonic mode, and **d** combination of dark and bright plasmonic modes in the case of asymmetric ($S$ = 190 nm)

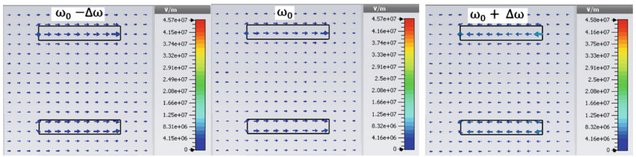
left to right at the PIR frequency $\omega_0$, and also it stays in the same circular direction at $\omega_0 + \Delta\omega$, which satisfies the mentioned condition. So we define the slot H-shape antenna as a bright mode. In contrast, the two slot strip antennas (Fig. 4b) appear as circular surface currents from left to right at $\omega_0 - \Delta\omega$, and they stay circular currents from left to right at PIR frequency $\omega_0$, while the surface currents in the two slot strips antennas are reversed at the reflectance peak after PIR frequency $\omega_0 + \Delta\omega_0$. In this case, the two slot strips antennas, i.e., the dark mode, appears unstable which implies that it is excited indirectly via near-field of the bright one at the PIR frequency $\omega_0$. Also, as it is clearly observable in Fig. 4d, when we have the combination of the dark and bright plasmonic modes in an asymmetric case ($S$ = 190 nm), the excited surface current changes in the dark mode after PIR frequency; but it is not changed in the bright one. The difference between direction and strength of the arrows around the two strips pair in Fig. 4b, d clearly shows that the dark mode can not excited directly and strongly with incident field (see Fig. 4b); but it can be excited indirectly and strongly via near field interaction with H-shape antenna (see Fig. 4d).

Planar metamaterial structures have been investigated in the past. In this work, we design a new planar metamaterial structure made of a silver thin-film layer and two cut-out antennas that shows a high reflectivity at infrared frequency regime more than other structures that are suggested in the previous study by N. Liu et al. [1]. As was explained in the introduction, coupling of the bright plasmonic mode with the incident light can cause a coupling of the dark plasmonic mode with the incident light that cannot couple to the normal incident light directly.

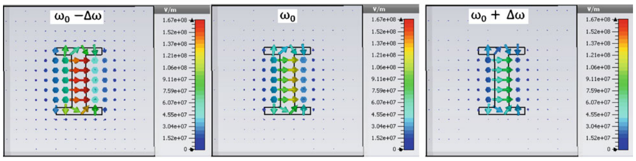
First, we consider the symmetric structure that was not predicted to lead to the PIR effect (in the case of $S$ = 0 nm) [1]. The simulated reflection (red-line curves), transmission (green-dashed curves), and absorption spectrum (blue-line curves) dependence on the lateral displacement $S$ are shown in Fig. 5. The absorption spectra (blue-line) are calculated using a standard relationship $A = 1\text{-}T\text{-}R$, where T and R denote the transmittance and reflectance, respectively. As shown in Fig. 5, when the structure is symmetric, there is only a resonance response in reflectance and transmittance spectrum. The physics behind of that is, there is only coupling between normal incident light and the bright plasmonic mode (dipole antenna) and no coupling with the dark plasmonic mode (quadruple antenna). It is clear that the slot strips pair does not contribute as the dipole and quadruple antennas are not coupled to each other in the absence of symmetry. We should break the symmetry of the H-II cut-out structure, in order that the net-induced current and the PIR effect is induced by excitation of SPRs in the coupling of the bright and dark modes [5]. Once we introduce anti-symmetric mode ($S \neq 0$), second-order mode started to be excited. As we can see in Fig. 5, in the case of $S$ = 30 nm, a reflectance peak at around $\omega_0 = 124$ THz emerges near the center of the broad resonance between 112 and 132 THz frequency range. With increasing asymmetry parameter ($S$) to 70 nm, the second-order mode is more excited and is more



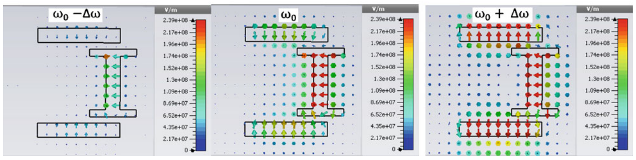
(a) Thin-Film



(b) Dark Plasmonic Mode



(c) Bright Plasmonic Mode



(d) Combination of Dark and Bright plasmonic modes at S=190 nm

**Fig. 4** Excited surface currents distributions at the reflectance peak $\omega_0$ and the two other frequencies near the PIR frequency $\omega_0 \pm \Delta\omega$, and the induced electric dipoles and quadruples are also depicted to clearly explain the physics of a coupled oscillator system for the case of **a** thin-film, **b** dark plasmonic mode, **c** bright plasmonic mode, and **d** combination of dark and bright plasmonic modes in the case of asymmetric structure ($S$ = 190 nm)

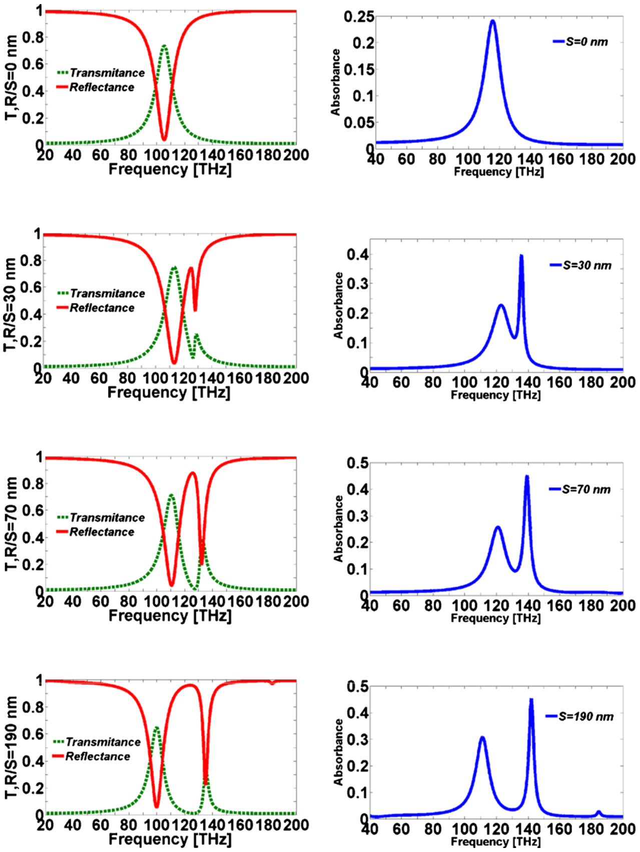


**Fig. 5** *Red-line*, *Green-dashed*, and *blue-line curves* represent the simulated results of reflectance and transmittance (**a**) and absorbance (**b**) spectra of the proposed planar metamaterial structure respectively

clearly seen in the reflectance spectrum. As the lateral displacement (asymmetry parameter) increases to 190 nm, the second narrow dip in reflectance is more enhanced than for the case of any other $S$ and also in this case, we have a high reflectance at an infrared frequency and in fact the PIR effect fully develops.

In general, the PIR effect appears when electric moments around the bright plasmonic mode are not equal. In order to better understand the underlying physics, the calculated electric field distributions at the resonance frequency in symmetric case ($S$ = 0 nm) and at the PIR frequency for one asymmetric case ($S$ = 190 nm) are presented in Fig. 6. When we consider a symmetric mode (i.e., $S$ = 0 nm), as can be seen in Fig. 6a, electric moments have the same magnitude but are in opposite directions; thus, they cancel each other out, and there is no net electric moment in the symmetric structure. Hence, we cannot see any PIR effect in the case of $S$ = 0 nm (see Fig. 5). Once introducing asymmetry ($S$ = 190 nm), electric moments around the bright plasmonic mode are not equal and as it is clear from Fig. 6b, one side of the bright plasmonic mode has an electric moment with a magnitude higher than the other side and in this state they cannot cancel each other out (although they have different directions with respect to each other). As a result, a net electric moment exists which induces circular currents or quadruple moments in the dark mode which results in the excitation of the plasmonic dark mode.

The other important feature in our proposed nanostructure is reduction in damping with respect to previous similar work [1]. In fact, for our proposed metamaterial in the near-infrared region, a higher reflection coefficient is achieved compared to the previous work [1]. We have used silver in our proposed metamaterial nanostructure and achieved a reflection coefficient higher than 90 % in the mentioned frequency region. This shows that damping is reached a minimum in the present structure. Addition of two H-shaped arms to the central bar in [1] has led to a stronger bright

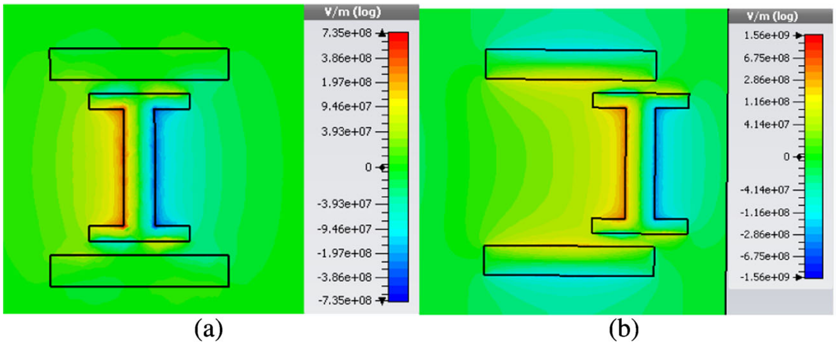


**Fig. 6** Z-component of electric field distributions in the PIR frequency for the case of **a** symmetric (i.e., $S = 0$ nm) and **b** asymmetric structure (i.e., $S = 190$ nm)

mode which has caused a lower damping and a higher reflection coefficient.

Up to now, all the results for our new planar metamaterial nanostructure are in a good agreement with the previous work [1], and also it shows our proposed nanostructure has great potential for infrared LSPR sensing applications, a benefit provided by the narrow linewidths and high modulation depths on the PIR features.

## Plasmonically Induced Reflectance in a Symmetric H-II Cut-Out Structure

In the previous section, we have demonstrated that broken symmetry is necessary to create PIR effect. Also, we have shown that in the presence of symmetry, there is no coupling between bright and dark plasmonic modes, and only one single resonance is observed in spectral response. The physical point behind is that broken symmetry allows strong coupling between slot antennas and to excite second-order modes leading to the PIR. Here, we suggest and demonstrate another possible mechanism to create the PIR effect in our planar metamaterial nanostructure in symmetric case. For achieving this new mechanism to observe the PIR even in symmetric case, the pair of slot strips is elongated to 1280 nm, which is less than three times the length of the slot strips used in the previous simulation in "Plasmonically Induced Reflectance in a Planar Metamaterial Structure with Broken Symmetry" section. The main reason for this elongation is that the higher-order modes could be excited as well as the fundamental mode. Also, we had to change $P_x$ and $P_y$ to 1300 nm from 850 nm because we increased L from 460 to 1280 nm.

At first, we have simulated the reflectance spectral response of the dark and bright plasmonic modes to normal incident light under the polarization that is described in previous section in Fig. 1. As is clearly observable in Fig. 7, the reflection spectrum of the dark plasmonic mode shows that it is still inactive when exposed to the normal incident light, where the reflection is nearly close to 1 due to no strong coupling with the external field. However, when the bright plasmonic mode and the dark one are combined, the PIR effect shows itself because the dark plasmonic mode is activated through the coupling with the bright one and by elongation of the length of slot strips pair (dark mode) even in the symmetric structure. This is not accessible when only the first-order mode is taken into account (notice the results in "Plasmonically Induced Reflectance in a Planar Metamaterial Structure with Broken Symmetry" section).

As clearly seen in Fig. 8, the calculated reflection, transmission, and absorption spectra for the symmetric case of $S = 0$ nm with different thickness of silver thin film, shows a clearer PIR effect and we have a high reflectivity in the symmetrical metamaterial structure. The physical mechanism behind that can be understood as follows. As mentioned in previous section, if the structure is symmetric, the electric components had exactly the same magnitude but were in opposite directions on both sides of the bright plasmonic mode, and thus they canceled each other out. But when we simulated the asymmetric mode (case of $S = 190$ nm), the electric components had opposite directions but not the same magnitudes and they induced a current or quadruple in the dark plasmonic mode (slot pair strips). This means

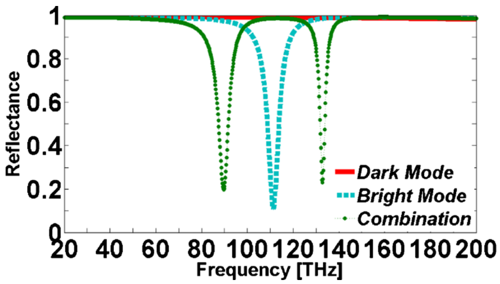
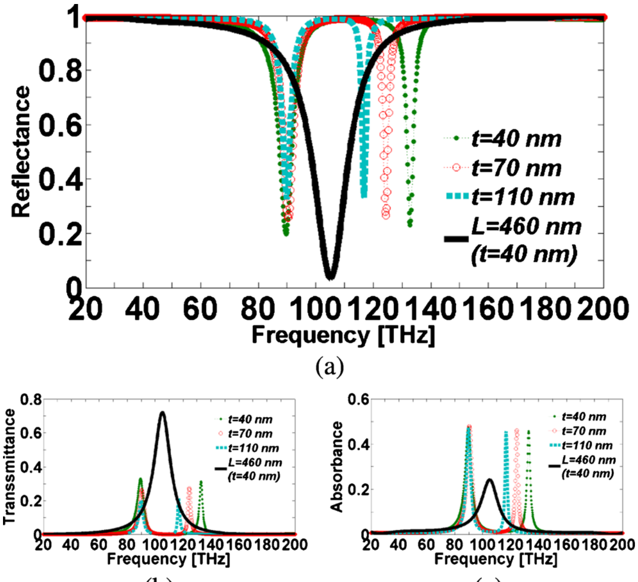


**Fig. 7** *Red-line, blue-dashed*, and *green-dotted curves* represent the simulated results of reflectance spectra of the dark, bright plasmonic mode, and combination of dark and bright plasmonic modes with each other for the symmetric case of proposed planar metamaterial structure respectively



(a)

(b)

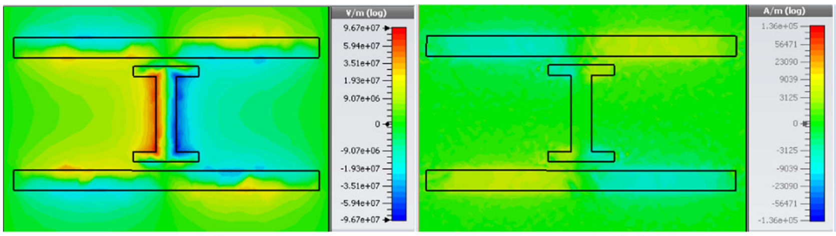
(c)

**Fig. 8** **a** Reflectance, **b** transmittance, and **c** absorption spectra with varying thickness of silver thin film $t$ for $L = 1280$ nm except the black-line curve for the state of $L = 460$ nm in symmetric case

excitation of the dark mode is really important. If the dark mode could be activated even in symmetric structure, the second-order mode can be excited and thus the PIR effect can be observed. Because of this important fact, we have increased the length of slot pair strips to excite the dark plasmonic mode without the need for broken symmetry. With this elongation, the dark mode is activated in our proposed planar metamaterial nanostructure and two antisymmetric quadruple resonances are induced on each side of the slot H-shape dipole antenna (bright plasmonic mode) by the two asymmetric electric field (see Fig. 9a). As a result, the excitation of the dark mode with the two circular currents, the PIR is achieved even in the symmetric structures. The physical mechanism behind of elongation of slot strips pair is that more room is provided to accommodate the two circular currents, thereby avoiding cancelation. Also, it is important to emphasize strength of the coupling can be tunned by changing the thickness of metal thin film. The thicker the film, the narrower is the peak (see Fig. 8).

To better understand the underlying physics, electric and magnetic field distributions in this proposed symmetric nanostructure are presented. As clearly observable in Fig. 9a, the Z-component of electric fields point in and out of xy plane on both sides of the bright plasmonic mode; and also because of the fact that the magnetic field is $\frac{\pi}{2}$ out of phase with the electric field [29], the X-component distribution of the magnetic field is illustrated in Fig. 9b with a $\frac{\pi}{2}$ phase difference compared to the electric field. As seen in the magnetic field distribution, the dark plasmonic mode (slot strips pair) is activated and two antisymmetric quadrupolar resonances are induced on each side of the bright plasmonic mode by the two antisymmetric electric fields of the dipole fields. As a result, with the excitation of the two circular currents, the PIR is also achieved in the symmetric structure. It is noteworthy to state that elongation of the length of slot strips pair caused to provide more room to accommodate the two circular currents, thereby avoiding cancelation. Thus, there is no

**Fig. 9** **a** Z-component of electric field distribution where the phase is 30° and **b** X-component of magnetic field distribution but with a phase of 120° in the PIR frequency for symmetric case with elongation the length of slot strips pair (i.e., $L = 1280$ nm)



(a)

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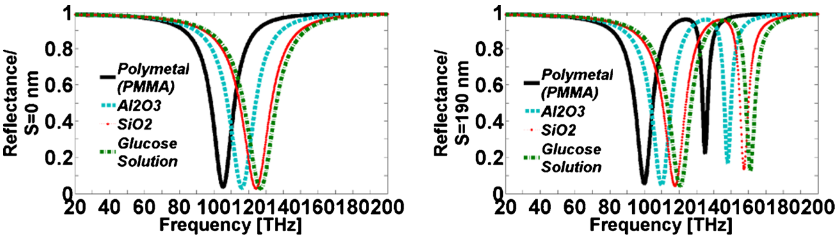


(a) (b)

**Fig. 10** *Black-line, blue-dashed, red-dotted*, and *green-dashed-dotted curves* represent the simulated results of reflectance spectra for polymetal dielectric (PMMA, $n = 2.15$), Al2O3 ($n = 1.76$), SiO2 ($n = 1.46$), and glucose solution ($n = 1.372$) respectively; for the case of **a** $S = 0$ nm and **b** $S = 190$ nm

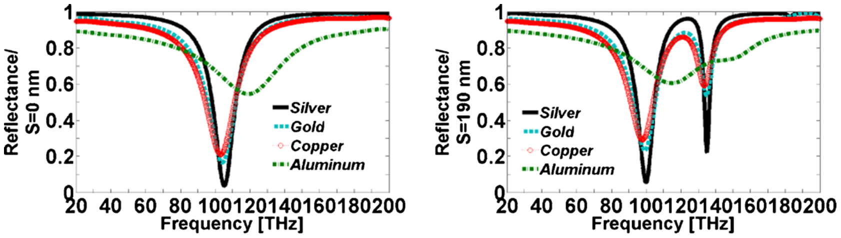
need to break the symmetry of the proposed metamaterial nanostructure to excite the second-order mode for appearance of the PIR. This possibility was previously showed as a candidate for plasmonic EIT in a multi-layer structure [15] but not for a planar metamaterial and the PIR effect.

In conclusion, the PIR can be achieved even in a planar metamaterial in symmetric state and it originates from excitation of the dark mode with elongation of the slot strips pair. Moreover, it is worthy to state that the higher-order of electric plasmon resonances (EPRs) are an important factor to excite the dark mode.

## Comparison of the Effect of Different Metals and Dielectrics on Spectral Response at PIR Frequency

Finally, we demonstrate that our proposed nanostructure may serve as a highly efficient localized surface plasmon resonance (LSPR) sensor in the near-infrared. For showing that, we have changed the dielectric surrounding of the silver nanostructure. It can be detected by measuring the shift of the sharp PIR feature. Figure 10 shows the simulation results when we have changed the dielectric. A clear shift of the reflectance peak to lower frequencies (longer wavelengths) is visible when we have changed the PMMA to glucose solution, SiO2 and Al2O3 due to the decrease of the refractive index of the material dielectric. As is clearly observable from Fig. 10, the resonance position depends very sensitively on the dielectric surrounding. Thus, decreasing of the refractive index from PMMA ($n = 2.15$) to glucose solution ($n = 1.372$) causes a blueshift of the PIR frequency. It shows sensitivity of resonance (PIR frequency) position on the dielectric surrounding. Consequently, the pronounced reflectance signal can be utilized as a promising measure of mass concentration for biochemically relevant molecules, for example, proteins, glucose, and DNA [1].

Also, in the last part of our study, we have investigated the effect of different metals on sensitivity of our proposed nanostructure in plasmonic sensing applications. As seen in Fig. 11, with changing the metals, the PIR frequency have changed slightly (a red-shift). When we have used silver, gold, and copper. But as obviously can be seen in Fig. 11b, for aluminum, we do not have a strong PIR effect in our planar metamaterial structure and also the PIR frequency has a blue-shift with respect to other metals used. In fact, the weaker PIR effect in aluminum in the near-infrared region in our proposed nanostructure is a result of higher plasma frequency of aluminum compared to other three metals used. Because aluminum's plasma frequency in the spectral region does not allow coupling of our proposed structure with the incident light. Considering dimensions used in our proposed nanostructure does not allow a strong coupling of the incident light with our metamaterial and leads to a lower reflection coefficient in the spectral response of Fig. 11. It should be mentioned that the broadening of the spectral response in Fig. 11 for aluminum is a result of the higher



(a) (b)

**Fig. 11** *Black-line, blue-dashed, red-empty-circles*, and *green-dashed-dotted curves* represent the simulated results of reflectance spectra for silver, gold, copper, and aluminum respectively; for the case of **a** $S = 0$ nm and **b** $S = 190$ nm collision frequency of aluminum compared to other three metals used in this work.

## Conclusion

In conclusion, we have theoretically investigated the plasmonically induced reflectance (PIR) in both symmetric and asymmetric planar metamaterial nanostructures in some detail. The generation of the PIR in asymmetric structure, confirmed further by the I-II cut-out structure and broken symmetry was necessary, which played a critical role in this phenomenon. In particular, we have demonstrated that the PIR can be realized even without broken symmetry via the excitation of higher-order EPR modes in a carefully designed planar plasmonic metamaterial. In fact, the necessity of asymmetry can be greatly relaxed if higher-order EPRs are taken into account. In addition, the narrow and fully modulated PIR features due to the extraordinary reduction of damping are exciting news for designing novel devices in the field of nano-photonic and also in metamaterial LSPR sensors with high sensitivities. The reflection and the width of the PIR peak in asymmetric structures are less than those in symmetric ones. In comparison with previous work [1], in our proposed nanostructure, the restrictions on size are partially relaxed, making fabrication much easier. Moreover, we have shown that the PIR frequency position depended very sensitively on the dielectric surrounding. Also, we investigated the effect of changing metals on reflectance spectral response. These results can be interesting and practical from both fundamental nanoplasmonic and application viewpoints. Finally, our proposed nanostructure can be used in superlensing [31] and plasmonic sensors [1].

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