Electromagnetic Induced Transparency and Slow light in Plasmonic Metasurfaces

Haseeb Ahmad Khan
UET: University of Engineering and Technology

Syed Waqar Shah
UET: University of Engineering and Technology

Adnan Daud Khan (✉ adnan.daud@uetpeshawar.edu.pk)
University of Engineering and Technology Peshawar  https://orcid.org/0000-0002-6579-4564

Research Article

Keywords: Plasmonic metasurfaces, EIT, Fano resonance, symmetry breaking, Figure of Merit, Group index

DOI: https://doi.org/10.21203/rs.3.rs-272442/v1

License: © This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License
Abstract

We report numerically electromagnetic-induced transparency (EIT) and Fano resonances in simple plasmonic metasurfaces consist of gold nanobars arranged in Pi, H and four shaped fashion. The bright and dark elements in the metasurfaces are responsible for the emergence of EIT and Fano effects in the transmission spectrum. The concept of symmetry breaking is also introduced by incorporating multiple cavities in the metasurface, which relaxes the dipole coupling selection rules resulting in a mixture of dipole and higher order modes that interact and engenders EIT and Fano modes simultaneously in a nanostructure. Furthermore, the EIT and Fano resonances experience a significant red-shift by increasing the refractive index of the background medium due to which high sensitivity of around 574 nmRIU, figure of merit of 32, and contrast ratio of 41% are realized. Moreover, the effective group index of the proposed metasurface is retrieved and is observed to be very high around the steep asymmetric Fano line shape and within the EIT window, signifying its potential use in slow light applications.

Introduction

Plasmonic nanoparticles exhibiting electromagnetic-induced transparency (EIT) and Fano resonances have received more consideration over the past few years due to their potential applications in high performance sensors [1], switching [2], and slow light devices [3]. The phenomena of EIT and Fano resonance are similar to one another, which emerges due to the interference of the wide continuum mode and narrow discrete mode (i.e. bright and dark modes) that modifies the properties of the medium by creating a narrow transparency window, where a very strong dispersion exist, which gives rise to slow light [4, 5]. Large group index or small group velocity can be attained only within the EIT window in slow light methodology, which stimulates the realization of the all-optical storage, where at various location information of several frequencies can be stored [6].

Zhang et al., was the first who realized the EIT effect theoretically in the metamaterials which consists of plasmonic resonators coupled in the nanoscale where maximum value of group index of 41 is achieved [7]. Consequently, Liu et al., was the first who proposed the EIT effect in the optical metamaterial experimentally, which consists of two functional layers, where each unit cell is stacked above two symmetric gold wires comprising of a gold bar [8]. Wang et al., proposed a planar structure, which contains of nanorod and nanoring where EIT effects are achieved by the bright-bright mode coupling of the ring/rod planar structure. The maximum value of Q-factor and group index was reached to 1.2 x 10^3 and 97, respectively [9]. Muhammad and Khan have analyzed a silicon planer structure with a cylindrical hole where low loss EIT resonance with a high value of local field enhancement of 33 and a Q factor of 584 are achieved [10]. Liu et al., have investigated the EIT effects in a metamaterial consisting of horizontal graphene wires and vertical gold strip in the terahertz region. Due to the lateral displacement of the structure the coupling of bright and dark modes takes place which results in the achievement of EIT effect. The recommended structure has the applications in detectors, sensors and modulators [11]. Sarkar et al., have proposed an asymmetric double C resonators (DCRs) structure and obtained a multiband EIT effect due to the strong field coupling between the bright and dark modes of the cut-wires
of the structure. The proposed study has applications in the development of buffers, modulators and slow light devices [12]. Recently, Li et al., have proposed a new type U-shaped coupled resonant structure, which provides strong EIT resonances that finds applications in tunable slow light devices [13].

In this paper, we demonstrate theoretically a simple metasurface of different shapes that supports EIT and Fano effects in the transmission spectrum. The strong interaction of the bright and dark plasmon modes supported by the nanorods leading to EIT and Fano resonances. The refractive index of the medium for the best structure is varied in order to evaluate its sensing performance and as a result high values of figure of merit, and contrast ratio are attained. Moreover, large group index of over 700 is achieved in the EIT window and around the Fano resonance, which results in the reduction factor for the group velocity.

**Geometry**

The schematic geometry of the metasurfaces are shown in Fig. 1. The pi-shaped structure shown in Fig. 1(a) is created by taking two vertical rods of width, $w=20$ nm and height, $H= 90$ nm and one Horizontal rod of width, $w= 85$ nm and height, $H=15$ nm. All the three rods are connected with one another and there is no space between the rods. Figure 1(b) illustrates the H shaped structure which is created by moving the horizontal rod of the pi-shaped structure to the central position. Figure 1(c) shows the four shaped (4-shaped) structure which is created by moving one of the vertical rods in the pi-shaped structure. All the metasurfaces are made of gold, whose dielectric function is taken from the experimentally measured Johnson and Christy data model [14]. The light is normally incident on the metasurface and the electric field polarization is taken along $x$-axis. For all the simulations, air is considered as the background medium. The COMSOL Multiphysics software which is based on three-dimensional finite element technique is used to carry out the entire simulations.

**Results And Discussion**

To analyze the effect of EIT resonances, we considered two cases of all the metasurfaces. In the first case, all the rods are connected while in the second case, all the rods have been disconnected.

**Connected Metasurfaces**

Figure 2(a, b) demonstrates the transmittance characteristics of a pi to H-shaped structure (see the inset). Since, the structure is polarization dependent, therefore, the plasmon resonances are examined for both the $x$- (Fig. 2(a)) and $y$-polarized (Fig. 2(b)) incident lights. In Fig. 2(a), the pi-shaped structure (position $D=0$nm) exhibit a single hybridized dipole mode at around 892 nm, which arises due to the coupling of plasmon modes supported by horizontal and vertical nanorods. In this case, the $x$-polarized light is not efficiently coupled with the nanostructure due to which a weak mode arises in the optical spectrum. As the value of the $D$ increases from 0nm, the dipole mode modifies i.e., its amplitude decreases and its spectral position is changed. At $D = 36$nm, the nanostructure adopts a H-shaped structure and the plasmon mode at the low wavelength region completely vanishes and another broad higher order mode
appears at around 1760 nm. In this transition from pi to H-shaped, no EIT resonance is obtained. For the $y$-polarized light (Fig. 2(b)), the plasmon modes of all the structures strongly couples with the incoming light due to which we obtained strong hybridized dipole mode as compare to the $x$-polarized case. For all the values of D, hybridized dipole mode strength remains the same, however with the increase in the value of D, blue-shift occurs in the spectrum. In this case also, no EIT resonance is obtained.

Figure 2(c, d) shows the transition from the pi-shaped to 4-shaped structure. Here, the transmittance characteristics are highly tuned by changing the variable 'E'. For the $x$-polarized case (Fig. 2(c)), when the value of E is increased, several higher order modes appear at the lower and higher wavelength regions. For instance, when $E = 30$ nm, a narrow higher order mode appears at 1265 nm whose amplitude increases significantly with the increase in the value of E. At $E = 45$ nm, another higher order narrow mode appears at low wavelength shoulder of the dipole mode, whose amplitude also increases with the increase in E. This higher order mode emerges because of the excitation of the bright and dark modes supported by the horizontal and vertical nanorods. In the previous case, only a single mode was obtained because in that structure, several mode cancellations occurred during coupling of plasmon modes supported by different rods. At $E = 75$nm, we obtained a 4-shaped structure, which exhibit clear higher order hybridized modes. Here, the higher order mode at 855nm, interact with the dipole mode at 909nm and induces an EIT at 874nm due to destructive interference. However, the strength of EIT mode is very weak because in this case, the incident light does not couple efficiently with the nanostructure. On the other hand, for the $y$-polarized light, strong plasmon modes are obtained for every value of E. Here again, for large value of E, two new modes at the low wavelength (873nm) and high wavelength (1240nm) regions are obtained. A narrow EIT resonance is generated at 880nm due to the coupling of narrow mode at 873 nm and dipole mode. At $E = 75$nm, this generated EIT resonance becomes more prominent and strong, where the nanoparticle fully adopts a 4-shaped structure. Thus, compared to all shapes, the 4-shaped structure exhibits strong EIT resonance, where a large group index can be realized, which prompts the achievement of the all-optical storage, where the different frequencies information at various positions can be accumulated [15].

Disconnected Structures

The structure symmetry is relaxed by incorporating several gaps (defects) inside the Pi, H and 4-shaped nanostructures, which excites multiple plasmon modes and EIT effects in the transmittance spectrum. These gaps result in the generation of higher order modes by dividing the structure into sub dipoles and making the structure disconnected.

We first investigated the transmittance characteristics of a disconnected Pi-shaped structure as shown in Fig. 3(a, b). For the $x$-polarized incident light (Fig. 3(a)), a new broad hybridized mode is obtained at the high wavelength region by increasing the value of the gap “g”. This mode appears due to the fact that by breaking the structure symmetry, different angular momenta modes strongly mix, allowing dark modes to get excited in the spectrum. In this case, the cavity modes and the modes of the nanorods interacts and excited dark modes in the transmission spectrum. Again, the resonances obtained for the $x$-polarized light
is weak due to weak coupling of light with the nanostructure. For the \( y \)-polarized case (Fig. 3(b)), the resonances obtained for all the values of \( g \) are approximately the same. Moreover, these modes are more or less similar to the connected H-shaped nanostructure (Fig. 2(b)).

Next, we considered the disconnected \( \Pi \)-shaped structure and converted it into H-shaped structure as shown in Figure 3(c, d). In this case, the width of the upper horizontal nanorod is taken as 30nm as shown in the inset. Here, for the \( x \)-polarized case, extremely weak resonances are obtained. For the \( y \)-polarized light, only a single dipole hybridized mode is attained for all values of \( L \). This indicates that these types of designs are not suitable for EIT effects. Figure 3(e, f) shows the transmittance spectra of \( \Pi \) to 4-shaped structure. In this case, the width of the upper horizontal nanorods is 85nm as shown in the inset. Multiple plasmon modes arise in the transmittance spectrum due to the following reasons: i) the structure symmetry is broken because of which the cavity modes and the modes supported by the metasurface which have different angular momenta interacts strongly with one another, ii) the modes exhibit by the metasurface and the metasurface in the nearby unit cell interacts and couple with one another.

Here, for the \( x \)-polarized light, when \( P = 100\text{nm} \), the broad mode at 930nm overlaps the narrow mode at 867nm and induces an asymmetric Fano line shape. The Fano resonance line shape is such that the location of its head is at the low wavelength shoulder of the narrow mode near 873nm and the location of its tail is at the high wavelength shoulder of the broad mode near 927nm. For \( P = 125\text{nm} \), the interaction of the broad mode at 1153nm and narrow mode at 1291nm engenders a Fano resonance with asymmetric line shape. However, the resonances in this case are very weak. For the \( y \)-polarized case, the structure exhibit strong multiple resonances as shown in Fig. 3(f). Here for \( P = 100\text{nm} \), a sharp Fano resonance produces due to the coupling of the broad mode at 925nm and the narrow mode at 873nm. This Fano resonance disappears at \( P = 125\text{nm} \) and a new Fano resonance with different asymmetric line shape appears at 1252nm. The induction of this Fano resonance is due to the destructive interference of the broad mode at 1170nm and the narrow mode at 1270nm. Moreover, a broad EIT resonance is also produced in this case at 1090nm due to coupling of the modes at 1013nm and 1170nm. Thus, in the disconnected 4-shaped structure, we attain both EIT and Fano effects, which may be highly suitable for slow light devices. Figure 3(g, h) shows the transmittance characteristics of the \( \Pi \) to 4-shaped structure, where the width of the upper horizontal nanobar is taken as 30nm. Here, unlike Fig. 3(f), no EIT or Fano resonances are found.

**Sensing Performance Evaluation**

The sensing ability of the metasurface is analyze for the connected \( \Pi \) to 4-shaped (CPFS) and disconnected \( \Pi \) to 4-shaped (DPFS) nanostructures for the \( y \)-polarized case. The sensitivity, figure of merit (FoM) and contrast ratio (CR) are usually used to determine the sensing performance [16]. Equation (1) is used to obtain the sensitivity by calculating the wavelength shift in the transmission peak when the refractive index ‘\( n \)’ of the embedding medium is changed. The FoM is the ratio of the sensitivity to the Bandwidth (BW) of the resonant mode which is calculated by using the Eq.(2). The Contrast ratio is the ratio of the difference between the peak value to the dip value divided by the sum of the peak value and the dip value which is calculated by using the Eq.(3). Fig. 4(a, b) illustrates the transmission spectra by
changing the refractive index of the surrounding medium. As demonstrated, increasing the refractive index of the medium results in a red shift in the resonant mode spectrum. Fig 4(c, d) illustrates the shift in the spectral modes at different values of the refractive indices. The EIT mode sensitivity in CPFS structure is 298 nmRIU\(^{-1}\), FOM and CR values are 32 and 41%. The EIT and Fano modes sensitivity in the DPFS structure are 472 nmRIU\(^{-1}\) and 574 nmRIU\(^{-1}\), FOM and CR values are 5.24, 7.0, 28.6% and 40.6%, respectively. The large sensing range indicates that the proposed metasurface can be used for sensing applications.

\[ \text{Sen} = \frac{\lambda_2 - \lambda_1}{n - 1} \] (1)

\[ \text{FoM} = \frac{\text{Sen}}{BW_{\lambda(1)}} \] (2)

\[ CR = \left| \frac{P_{\text{value}} - D_{\text{value}}}{P_{\text{value}} + D_{\text{value}}} \right| \] (3)

**Group index properties**

The proposed structure is analyzed for the slow light effect using group index properties. The complex scattering coefficients through the metasurface can be used to retrieve these effective properties [17]. It is to be noted that a single unique solution exists for homogenized effective refractive index medium for a nanostructure with a given thickness which shows the similar far field complex scattering parameters i.e., transmission and reflection. The absorption and amplitude/phase of transmission/reflection through the nanostructure entirely satisfy our retrieved wave impedance \( z \) and complex refractive index \( n \).

Furthermore, the position of the reference plane to our physical nanostructure is along the top and bottom i.e. thickness of the effective medium is same as the metal physical thickness. Here, it is stressed that none of the other reference planes should provide the same absorption and scattering properties by satisfying the homogenized refractive index. Figure 5 demonstrates the group index characteristics for the best cases i.e., CPFS and DPFS metasurfaces. We first used the retrieval method for calculating the refractive index \( n \) of a homogenous slab as illustrated in Ref. [18]. The relation \( n_g(\lambda) = n(\lambda) + \lambda \frac{\partial n(\lambda)}{\partial \lambda} \) is used for calculating the effective group index. It is observed that the corresponding group index and spectral position of the EIT and Fano resonance almost remain unchanged. The maximum group index for CPFS metasurface is around 700 at EIT resonance (Fig. 5(a)), while for the DPFS metasurface (Fig. 5(b)), the slow light factor is around 53 at EIT and 265 at Fano resonance, respectively. These results show that the proposed structure can be useful for slow light devices.

**Conclusion**

The generation of EIT and plasmonic Fano resonances in a Pi, H and 4-shaped gold metasurfaces have been studied. The horizontal and vertical nano bars of gold metasurface supports bright and dark modes
whose interaction with one another arises EIT and Fano resonances. The defects are incorporated in the connected metasurface in order to break the symmetry of the structure, which results in a mixing of modes having different angular momentum and engenders EIT and Fano effects in a single nanostructure. The sensing performance of the connected Pi to 4-shaped structure (CPFS) and disconnected Pi to 4-shaped structure (DPFS) for y-polarized incident light are calculated and high values of sensitivity, FoM and CR are achieved that can reach as high as 574 nmRIU$^1$, 32 and 41%, respectively, which suggests that the proposed structure is highly suitable for sensing applications. Furthermore, the group index spectra is also calculated and highest value around 700 within the EIT window and around Fano resonance is attained, which indicates that the photons can be deceived for long time within the metasurface, making it suitable for slow light applications.

Declarations

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of interest/Competing interests

- The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
- The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Availability of data and material

Not applicable.

Code availability

Not applicable.

Authors' contributions

Conceptualization, A.D.K. and H.A.K.; methodology, A.D.K.; software, H.A.K.; validation, S.W.S., A.D.K. and H.A.K.; formal analysis, H.A.K.; investigation, H.A.K. and S.W.S.; resources, H.A.K.; data curation, H.A.K.; writing—original draft preparation, A.D.K.; writing—review and editing, S.W.S.; visualization, H.A.K.; supervision, A.D.K.; project administration, A.D.K.; funding acquisition, S.W.S.
Ethical Statement

Hereby, I Adnan Daud Khan consciously assure that for the manuscript titled “Electromagnetic Induced Transparency and Slow light in Plasmonic Metasurfaces” the following is fulfilled:

1) This material is the authors’ own original work, which has not been previously published elsewhere.

2) The paper is not currently being considered for publication elsewhere.

3) The paper reflects the authors' own research and analysis in a truthful and complete manner.

4) The paper properly credits the meaningful contributions of co-authors and co-researchers.

5) The results are appropriately placed in the context of prior and existing research.

6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.

7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

The violation of the Ethical Statement rules may result in severe consequences.

I agree with the above statements and declare that this submission follows the policies of Plasmonics Journal as outlined in the Guide for Authors and in the Ethical Statement.

Date: 25/02/2021

Corresponding author:

Adnan Daud Khan,

Director – Center for Advanced Studies in Energy

University of Engineering & Technology,

Pakistan.

Email: adnan.daud@uetpeshawar.edu.pk

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Consent for publication
There are no case studies involve in the current work. Therefore, this declaration is not applicable in our case.

References

[1] A. D. Khan, "Refractive index sensing with fano resonant L-shaped metasurface," *Optical Materials*, vol. 82, pp. 168-174, 2018.

[2] H. Mbarak, R. T. Ghahrizjani, S. Hamidi, E. Mohajerani, and Y. Zaatar, "Reversible and tunable photochemical switch based on plasmonic structure," *Scientific Reports*, vol. 10, pp. 1-7, 2020.

[3] D. Cheng, P. Yu, L. Zhu, X. Yu, X. Tang, S. Zhan, *et al.*, "Coupled Mode Demonstration of Slow-Light Plasmonic Sensor Based on Metasurface at Near-Infrared Region," *Plasmonics*, vol. 15, pp. 1389-1394, 2020.

[4] C. Cen, J. Chen, C. Liang, J. Huang, X. Chen, Y. Tang, *et al.*, "Plasmonic absorption characteristics based on dumbbell-shaped graphene metamaterial arrays," *Physica E: Low-dimensional Systems and Nanostructures*, vol. 103, pp. 93-98, 2018/09/01/ 2018.

[5] J. Ren, G. Wang, W. Qiu, Z. Lin, H. Chen, P. Qiu, *et al.*, "Optimization of the Fano Resonance Lineshape Based on Graphene Plasmonic Hexamer in Mid-Infrared Frequencies," *Nanomaterials (Basel, Switzerland)*, vol. 7, p. 238, 2017.

[6] S. Fu, X. Zhang, Q. Han, S. Liu, X. Han, and Y. Liu, "Blu-ray-sensitive localized surface plasmon resonance for high-density optical memory," *Scientific reports*, vol. 6, p. 36701, 2016.

[7] M. Amin, R. Ramzan, and O. Siddiqui, "Slow Wave Applications of Electromagnetically Induced Transparency in Microstrip Resonator," *Scientific Reports*, vol. 8, p. 2357, 2018/02/05 2018.

[8] N. Liu, L. Langguth, T. Weiss, J. Kästel, M. Fleischhauer, T. Pfau, *et al.*, "Plasmonic analogue of electromagnetically induced transparency at the Drude damping limit," *Nature Materials*, vol. 8, pp. 758-762, 2009/09/01 2009.

[9] J. Wang, B. Yuan, C. Fan, J. He, P. Ding, Q. Xue, *et al.*, "A novel planar metamaterial design for electromagnetically induced transparency and slow light," *Optics Express*, vol. 21, pp. 25159-25166, 2013/10/21 2013.

[10] N. Muhammad and A. D. Khan, "Tunable Fano Resonances and Electromagnetically Induced Transparency in All-Dielectric Holey Block," *Plasmonics*, vol. 10, pp. 1687-1693, 2015/12/01 2015.

[11] C. Liu, P. Liu, L. Bian, Q. Zhou, G. Li, and H. Liu, "Dynamically tunable electromagnetically induced transparency analogy in terahertz metamaterial," *Optics Communications*, vol. 410, pp. 17-24, 2018/03/01/ 2018.
[12] R. Sarkar, D. Ghindani, K. M. Devi, S. S. Prabhu, A. Ahmad, and G. Kumar, "Independently tunable electromagnetically induced transparency effect and dispersion in a multi-band terahertz metamaterial," *Scientific Reports*, vol. 9, p. 18068, 2019/12/02 2019.

[13] Q. Li, S. Liu, X. Zhang, S. Wang, and T. Chen, "Electromagnetically induced transparency in terahertz metasurface composed of meanderline and U-shaped resonators," *Optics Express*, vol. 28, pp. 8792-8801, 2020/03/16 2020.

[14] P. B. Johnson and R.-W. Christy, "Optical constants of the noble metals," *Physical review B*, vol. 6, p. 4370, 1972.

[15] M. Zhao, H. Xu, C. Xiong, B. Zhang, C. Liu, W. Xie, *et al.*, "Tunable slow light effect based on dual plasmon induced transparency in terahertz planar patterned graphene structure," *Results in Physics*, vol. 15, p. 102796, 2019.

[16] Y. H. Fu, J. B. Zhang, Y. F. Yu, and B. Luk'yanchuk, "Generating and Manipulating Higher Order Fano Resonances in Dual-Disk Ring Plasmonic Nanostructures," *ACS Nano*, vol. 6, pp. 5130-5137, 2012/06/26 2012.

[17] A. Khan and M. Amin, "Multispectral broadband PIT and Fano resonance in skewed dipolar metasurface," *Optical Materials*, vol. 79, pp. 480-487, 2018.

[18] D. Smith, D. Vier, T. Koschny, and C. Soukoulis, "Electromagnetic parameter retrieval from inhomogeneous metamaterials," *Physical review E*, vol. 71, p. 036617, 2005.

**Figures**

---

**Figure 1**

![Image of diagrams](image-url)
Schematic of a. Pi-Shaped, b. H-Shaped, and c. 4-Shaped nanostructures.

**Figure 2**

Transmission characteristics of connected structures a. Pi to H-shaped structure for Ex polarization b. Pi to H-shaped structure for Ey polarization c. Pi to 4-shaped structure for Ex polarization, and d. Pi to 4-shaped structure for Ey polarization.
Figure 3

Transmission characteristics of disconnected structures a, b. Pi-shaped structure polarization is along Ex and Ey c, d. pi to 4-shaped structure polarization is along Ex and Ey e, f. Modified Pi to H-shaped structure polarization is along Ex and Ey g, h. Modified Pi to 4-shaped structure polarization is along Ex and Ey.
**Figure 4**

a, b. Transmission Spectra for different refractive indices sensitivity for CPFS and DPFS nanostructures.

c, d. Wavelength shifts versus refractive index.

**Figure 5**

Group index spectra of CPFS and DPFS metasurfaces.