Optics and Photonics Journal, 2021, 11, 79-88
https://www.scirp.org/journal/opj
ISSN Online: 2160-889X
ISSN Print: 2160-8881

A Metamaterial Design Based on Electromagnetic Induction Transparency-Like Effect and Its Slow-Wave Performance

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How to cite this paper: Xu, Z. (2021) A Metamaterial Design Based on Electromagnetic Induction Transparency-Like Effect and Its Slow-Wave Performance. *Optics and Photonics Journal*, **11**, 79-88.
https://doi.org/10.4236/opj.2021.114006

Received: March 31, 2021
Accepted: April 18, 2021
Published: April 21, 2021

Abstract

This paper proposes a new metamaterial design that can achieve electromagnetic induction transparency-like (EIT-like) effects in the microwave band. The unit structure of metamaterials consists of square rings and metal wires. The square ring acts as the “bright state” and the metal wire acts as the “dark state”. The destructive interference between the bright state and the dark state produces an EIT-like effect. In the simulation results, a transparent window centered at 4.00 GHz can be observed in the transmission spectrum. By studying the phase change of the transparent window, it is found that the group delay of the metamaterial structure can reach 0.39 ns at 4.00 GHz. This paper also studies the influence of the refractive index of the medium on the EIT-like effect. Numerical simulations show that such metamaterial is very sensitive to the refractive index of the medium, and the sensitivity is 15 mm/RIU. Our design can be extended to other frequency bands and may have potential applications in filtering, sensing, slow-light devices, and nonlinear optics.

Keywords

Electromagnetically Induced Transparency-Like, Metamaterial, Slow-Wave, Near-Field Coupling

1. Introduction

In quantum optics, the absorption line of an atomic medium is determined by the energy level structure of the atom. When the frequency of the incident light is the same as the transition frequency of the electron at the atomic level, the incident light is absorbed and the atomic medium is opaque. In atomic systems, the destructive interference between two quantum transition channels will cause the absorption of light at the resonance frequency of the atom to be suppressed, creating a transmission window [1], which is a quantum coherence phenomenon in the atomic system called the electromagnetic induction transparency (EIT) effect [2]-[7]. This effect generally produces extremely strong anomalous dispersion, resulting in a large reduction in group velocity [8]-[13]. At the EIT frequency, the intensity of the electric field is strong, which greatly enhances the nonlinear effect. Therefore, these effects have a very wide application prospect in the fields of quantum information storage and nonlinear optics [14]. However, the experimental conditions required for these quantum optics experiments are harsh, such as extremely low temperatures, extremely intense magnetic fields. This greatly limits the practical application of quantum EIT [15]. In recent years, researchers have paid more attention to the EIT-like effects in non-quantum systems [16] [17] [18].

Metamaterials are composed of sub-wavelength localized resonant electromagnetic units called "artificial atoms" [19]. And it can be used in classical systems to mimic EIT in quantum systems. The appearance of metamaterials has also broken through the application limits of conventional materials. Because of their special physical properties, metamaterials have become the focus of scientific research in many countries. Metamaterials have great potential applications in many fields, such as medical, military, biological, chip manufacturing, and so on. On the one hand, metamaterials have shown powerful abilities to control electromagnetic waves, such as negative refraction [20] [21] and invisibility cloaks [22] [23]. On the other hand, the metamaterials provide a universal platform for studying new wave phenomena in condensed matter and atomic systems [24]. Inspired by new concepts in condensed matter physics and quantum optics, the results of the study of classical wave phenomena in metamaterials may provide new ideas and advanced techniques for wave manipulation and wave matter interactions. Typical examples of this research direction include the realization of photonic topological insulator lasers [25], silicon valley photonic routers [26], and wave delay [27] and storage [28] based on the EIT-like effect of metamaterials.

This paper proposes a new scheme to realize the EIT-like effects. The unit structure of this metamaterial consists of two square rings and two metal wires, in which the square ring acts as the "bright state" and the wire acts as the "dark state". After carefully adjusting the geometric parameters, the destructive interference between the square ring and the wire can result in an EIT-like effect. The numerical simulation results show that our EIT-like metamaterial presents transparent windows around 4.00 GHz with 0.39 ns slow-wave group delay time in 1.0 mm thicknesses. Slow-wave is an important application of the EIT-like effect. The EIT-like effect can prolong the propagation time of the signal in thin media. This time is called the group delay. The principle is to make use of the EIT-like effect to cause larger refractive index changes in the narrow frequency range, thus realizing slow wavelets. Finally, this paper analyzes the influence of the refractive index of the medium on the EIT-like effect. The results show that the transmission peak frequency is linearly related to the refractive index of the medium. The sensitivity of the results to the refractive index of the medium is 15 mm/RIU. The results show that the structure can be widely used in slow-wave devices and refractive index sensors [29] [30] [31] [32].

2. Design and Method

The geometrical structure of the EIT-like metamaterials is shown in **Figure 1(a)**. It consists of metal wires and square rings. The unit structures are arranged periodically on the substrate. The substrate is made of FR-4 whose permittivity is 4.3, the thickness is 1 mm, and the size is 30 mm × 30 mm. This is a composite material composed of epoxy resin, filler, and glass fiber, which is often used to make microwave substrates because of its stable insulation and low cost. The unit structure of this EIT-like metamaterial is shown in **Figure 1(b)**. The metal structures are made of copper with a thickness is 0.035 mm. Geometric parameters of the metamaterial are a = 2 mm, d = 22 mm, m = 1 mm, n = 8 mm, l = 28 mm, h = 30 mm.

In this paper, CST electromagnetic simulation software is used to simulate the electromagnetic field. The Finite-Difference Time-Domain (FDTD) method used in CST simulation software is also one of the most common methods in microwave calculation. In the simulation process, periodic boundary element conditions were used to calculate the transmission lines, group delay, and surface current distribution of the EIT-like metamaterials.

3. Results and Discussion

When the electromagnetic wave incident along the negative direction of the z-axis, the polarization direction of the electric field is in the negative direction of the x-axis, and the magnetic field is in the positive direction of the y-axis, the transmission spectrum of the metal wire, square ring and the EIT-like metamaterials

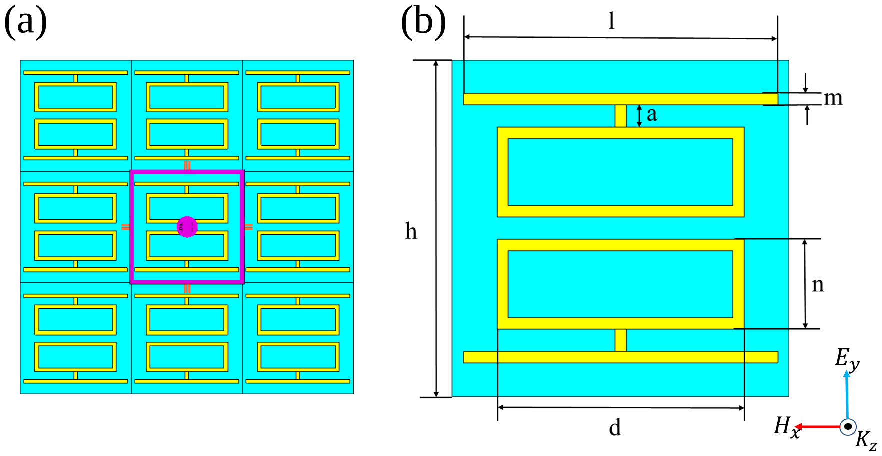

Figure 1. (a) Schematic of the EIT-like metasurface structure; (b) Schematic of the cell structure of the metasurface, a = 2 mm, d = 22 mm, m = 1 mm, n = 8 mm, l = 28 mm, h = 30 mm.

are shown in Figure 2. The square ring can be directly and strongly excited by the incident wave, and resonates strongly near 4.19 GHz, acting as a "bright state" in this structure, while the wire cannot be directly excited by the incident wave.

Figure 3 shows the surface current distribution under the incident electromagnetic wave when the square ring and the metal wire exist separately. It can be seen that a large amount of current is concentrated on the square ring, while almost no surface current exists on the metal wire. This is also consistent with the transmission spectrum above, which further confirms that the square ring acts as a "bright state" and the metal wire acts as a "dark state" in this structure. As shown in Figure 2, when they are combined, the transmission spectra appears a transparent window centered at 4.00 GHz, and the transmittance can

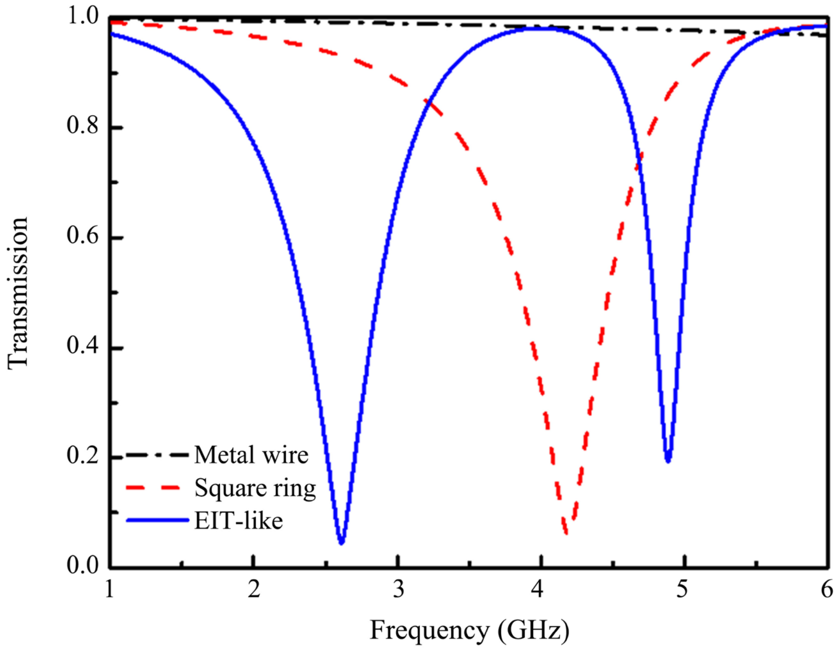

Figure 2. Transmission spectra of metal wire, square ring, and EIT-like metamaterials.

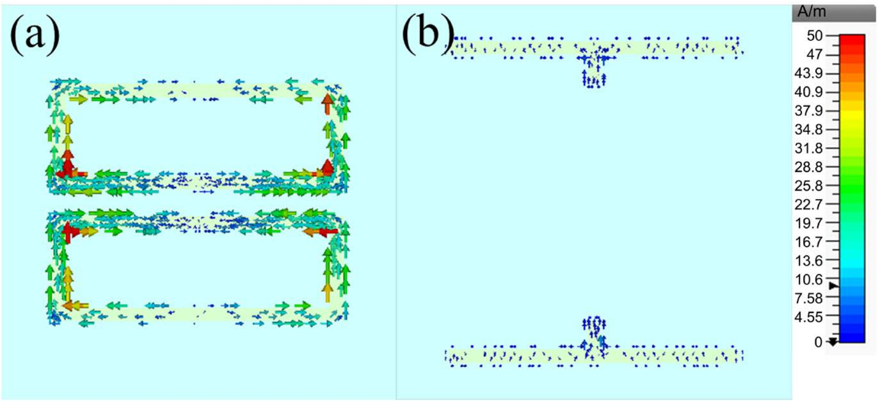

Figure 3. Surface current distribution of square ring (a) and metal wire (b) at the resonant frequency. The closer the color is to red, the stronger the surface current intensity.

reach 98%. Two obvious transmission valleys were also observed at 2.61 GHz and 4.89 GHz. The appearance of the transparent window marks the formation of the EIT-like effect. The reason is that when the metamaterial formed by the combination of metal wire and square ring is incident by the electromagnetic wave, the destructive interference will occur between the "bright state" and "dark state", and the transparent window similar to the EIT effect in the atomic system will also appear. *Q*-factor can be calculated by Equation (1):

$$Q = \frac{f_0}{\text{FWMH}} \tag{1}$$

In this formula, f_0 represents the frequency at the transmission peak of the transparent window with EIT-like effect, and FWMH represents the half-height and half-width of the transmission peak. The transmission peak frequency of the transmission spectral line is 4.00 GHz, the half-height width is 1.69 GHz, and the calculated *Q*-factor is 2.37

3.1. Surface Current Analysis

To more clearly study the physical mechanism and coupling of the EIT-like effect of the metamaterial, the surface current distribution of the structure at the transmission peak and two transmission valley frequencies was obtained through simulation, as shown in **Figure 4**.

As can be seen from **Figure 4(a)**, at the low-frequency transmission valley, the current is mostly concentrated on the two square rings, while there is almost no current on the metal wires. This is because the electric field polarization direction of the incident wave is in the y-axis direction, and the magnetic field polarization direction is in the x-axis direction. In this direction, the metal wire cannot be coupled with the incident wave, while the square ring can be directly excited by the incident wave to produce resonance. Due to the symmetry of the metamaterial structure, the ideal magnetic wall is centered in the horizontal direction of the square ring, so the surface currents on the left and right sides of the square rings are in opposite directions. **Figure 4(b)** shows the surface current distribution at the transmission peak at 4.00 GHz. It can be seen that a strong current also appears on the metal wire, and the direction is opposite to the direction of the surface current on the square ring. This is because near-field

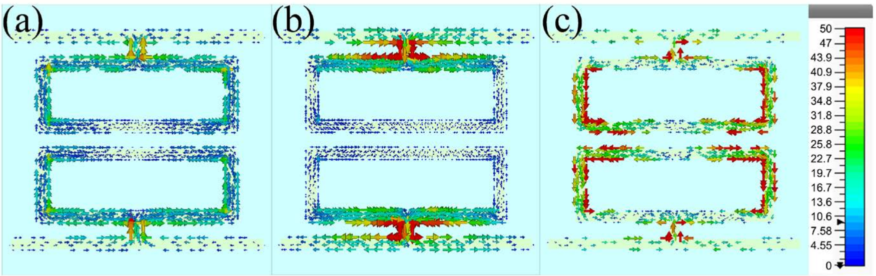

Figure 4. Surface current distribution at low frequency transmission valley 2.61 GHz (a), transmission peak 4.00 GHz (b) and high frequency transmission valley 4.89 GHz (c).

coupling occurs between the square ring and the metal wire at the transmission peak, so that the square ring couples energy to the metal wire. The antiparallel currents excited by the external field and the induced field produce destructive interference in the structure, so the current on the square ring is suppressed, and the current on the metal wire is enhanced. From the surface current distribution at the high-frequency transmission valley, it can be seen that there are still anti-parallel currents on the metal wire and the square ring, but the current on the device in the vertical direction is significantly stronger than the device in the horizontal direction. This is because the device in the vertical direction is the same as the electric field direction.

3.2. Slow-Wave Performance

Slow-wave is an important application of the EIT-like effect. The effect can prolong the transmission time of the signal in the ultra-thin medium, which is called the Group delay. Because the dispersion characteristic of the medium determines the group velocity of light propagation in the medium. The refractive index of the material changes with the frequency of the incident wave. This characteristic affects the propagation speed of light. When the EIT-like effect occurs, strong normal dispersion will follow. The refractive index of the material will be changed greatly in a narrow frequency range, thereby slowing down the group velocity of light propagation. The transmission time of light in the medium will be prolonged, and the slow wave effect will appear.

Figure 5(a) shows the transmission phase change of the structure. The phase changes dramatically at the resonant frequency. At the EIT-like transparent window, the phase change can cause strong normal dispersion, which slows down the propagation speed of the incident wave in the medium, causing group delay and realizing the slow-wave effect. The group delay spectrum of the metamaterial structure is shown in Figure 5(b). The maximum group delay can reach 0.39 ns. An important parameter to evaluate slow-wave performance is the Delay Bandwidth Product (DBP), which is defined as:

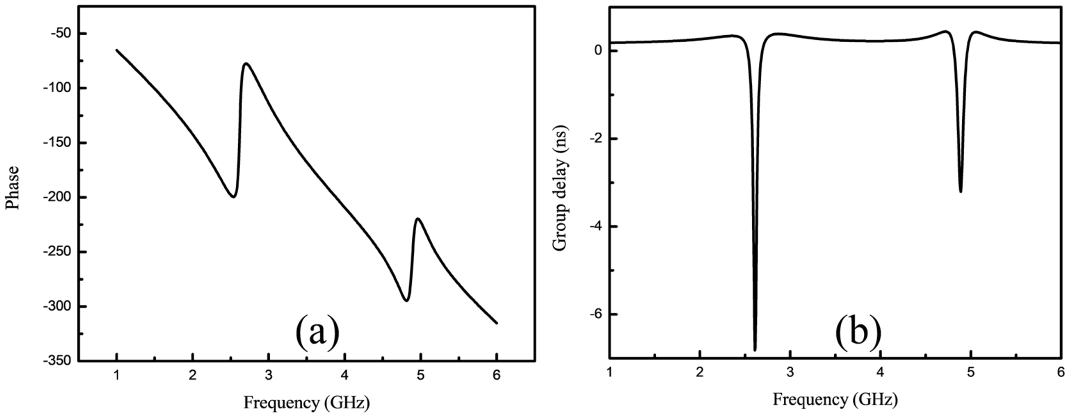

Figure 5. (a) Transmission phase change of metamaterial structure; (b) Group delay spectrum of this metamaterial structure.

$$\text{DBP} = \tau_g \times \Delta f\ . \tag{2}$$

τ_g represents the maximum group delay that can be realized by the structure, and Δf represents the half-height and half-width of the transmitted spectral line. The maximum group delay of the structure is 0.39 ns, and the half-height width is 1.69 GHz, so the DBP is calculated as 0.659. The research results show that the metamaterial has potential application value in slow-wave devices.

3.3. Influence of Medium Refractive Index on EIT-Like Effect

One potential application of EIT-like metamaterials is sensors. When the refractive index of the environment is changed, the resonance frequency of metamaterials tends to shift. To study the sensing characteristics of this structure, this paper set the refractive index of the medium in which the metamaterial is located to slowly change from 1 to 1.1. The transmission spectrum of the metamaterials under different media refraction has been obtained by simulation, as shown in **Figure 6(a)**. It can be found that with the increasing refractive index of the medium, the resonance frequency of the metamaterial moves to a low frequency. Although the increase in the refractive index of the medium is small, the resonance frequency is significantly shifted.

This paper can evaluate the sensing sensitivity of metamaterial structure by using the frequency shift of transmission peak corresponding to each refractive index unit (RIU). **Figure 6(b)** shows the relationship between the frequency of transmission peak and the refractive index of the medium. The black is the simulated data, and the red is the linear fitting. It is found that the frequency of transmission peak is linearly correlated with the refractive index of the medium. The absolute value of the slope represents the sensitivity of the structure to the refractive index of the medium, which can be calculated as follows:

$$S = \frac{\mathrm{d}f}{\mathrm{d}n}\ . \tag{3}$$

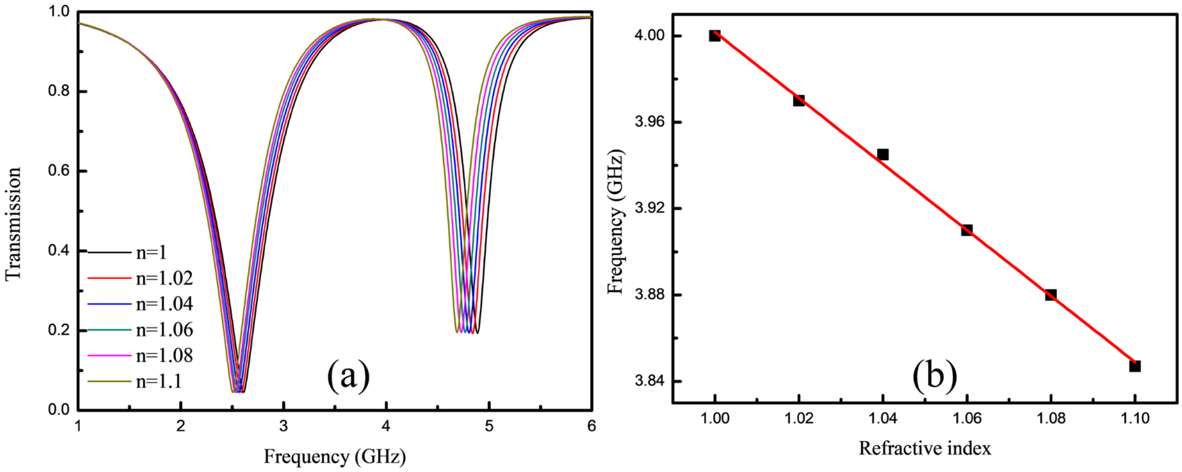

Figure 6. (a) Transmission spectrum of the metamaterial structure under different medium refractive index; (b) The relationship between EIT-like transmission peak frequency and the refractive index of the medium.

The sensitivity was calculated to be 15 mm/RIU. Through the study of the sensitivity of the metamaterial to the refractive index of the medium, it can be proved that the structure is very sensitive to the refractive index of the medium, and can be applied to the refractive index sensor.

4. Conclusion

In this study, this paper proposes a metamaterial structure consisting of square rings and metal wires, which can realize the EIT-like effect. The square ring can be directly excited by incident waves to act as a "bright state". However, the wire cannot be excited and only be excited through the near-field coupling of the "bright state", so it is regarded as the "dark state". By analyzing the surface current distribution of the metamaterial at the resonance frequency, the researchers clearly understand the physical reasons for the appearance of the EIT-like effect and the coupling mechanism in the structure. The destructive interference between the square ring and the wire leads to the emergence of the EIT transparent window. By studying the slow-wave properties of the metamaterial, it is found that the maximum group delay of the structure reaches 0.39 ns, which has a very important application value in slow light devices. Finally, this paper measures the sensing sensitivity of the metamaterial structure by studying the influence of medium refractive index on the EIT-like effect. It is found that the structure is very sensitive to the refractive index of the medium in which it is located, with a sensitivity of 15 mm/RIU, which can be applied to some refractive index sensors. This article provides a new design for the realization of EIT-like effects and can be expanded to other frequency bands by adjusting the size. The metamaterial has potential application value in the fields of slow-wave devices, optical sensing, and optical storage.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Boller, K.J., Imamoğlu, A. and Harris, S.E. (1991) Observation of Electromagnetically Induced Transparency. *Physical Review Letters*, **66**, 2593. https://doi.org/10.1103/PhysRevLett.66.2593

[2] Meng, F.Y., Wu, Q., Erni, D., *et al.* (2012) Polarization-Independent Metasurface Analog of Electromagnetically Induced Transparency for a Refractive-Index-Based Sensor. *IEEE Transactions on Microwave Theory and Techniques*, **60**, 3013-3022. https://doi.org/10.1109/TMTT.2012.2209455

[3] Mun, S.E., Lee, K., Yun, H., *et al.* (2016) Polarization-Independent Plasmon-Induced Transparency in a Symmetric Metasurface. *IEEE Photonics Technology Letters*, **28**, 2581-2584. https://doi.org/10.1109/LPT.2016.2605740

[4] Lu, W.B., Liu, J.L., Zhang, J., *et al.* (2016) Polarization-Independent Transparency Window Induced by Complementary Graphene Metasurfaces. *Journal of Physics D*:

Applied Physics, **50**, Article ID: 015106.
https://doi.org/10.1088/1361-6463/50/1/015106

[5] Wang, W., Li, Y., Xu, P., *et al.* (2014) Polarization-Insensitive Plasmonic-Induced Transparency in Planar Metasurface Consisting of a Regular Triangle and a Ring. *Journal of Optics*, **16**, Article ID: 125013.
https://doi.org/10.1088/2040-8978/16/12/125013

[6] Guo, B.S., Loo, Y.L. and Ong, C.K. (2017) Polarization Independent and Tunable Plasmonic Structure for Mimicking Electromagnetically Induced Transparency in the Reflectance Spectrum. *Journal of Optics*, **19**, Article ID: 105101.
https://doi.org/10.1088/2040-8986/aa82cb

[7] Hao, Z., Gao, Y., Huang, Z., *et al.* (2017) Polarization-Independent Magneto-Electric Fano Resonance in Hybrid Ring/Disk Hetero-Cavity. *Journal of Optics*, **19**, Article ID: 125002. https://doi.org/10.1088/2040-8986/aa952a

[8] Kang, M., Li, Y.N., Chen, J., *et al.* (2010) Slow Light in a Simple Metasurface Structure Constructed by Cut and Continuous Metal Strips. *Applied Physics B*, **100**, 699-703. https://doi.org/10.1007/s00340-010-4184-6

[9] Meng, F.Y., Fu, J.H., Zhang, K., *et al.* (2011) Metasurface Analogue of Electromagnetically Induced Transparency in Two Orthogonal Directions. *Journal of Physics D: Applied Physics*, **44**, Article ID: 265402.
https://doi.org/10.1088/0022-3727/44/26/265402

[10] Fleischhauer, M., Imamoglu, A. and Marangos, J.P. (2005) Electromagnetically Induced Transparency: Optics in Coherent Media. *Reviews of Modern Physics*, **77**, 633.
https://doi.org/10.1103/RevModPhys.77.633

[11] Thuy, V.T.T., Tung, N.T., Park, J.W., *et al.* (2010) Highly Dispersive Transparency in Coupled Metasurfaces. *Journal of Optics*, **12**, Article ID: 115102.
https://doi.org/10.1088/2040-8978/12/11/115102

[12] Tidström, J., Neff, C.W. and Andersson, L.M. (2010) Photonic Crystal Cavity Embedded in Electromagnetically Induced Transparency Media. *Journal of Optics*, **12**, Article ID: 035105. https://doi.org/10.1088/2040-8978/12/3/035105

[13] Garrido Alzar, C.L., Martinez, M.A.G. and Nussenzveig, P. (2002) Classical Analog of Electromagnetically Induced Transparency. *American Journal of Physics*, **70**, 37-41.
https://doi.org/10.1119/1.1412644

[14] Lvovsky, A.I., Sanders, B.C. and Tittel, W. (2009) Optical Quantum Memory. *Nature Photonics*, **3**, 706-714. https://doi.org/10.1038/nphoton.2009.231

[15] Phillips, D.F., Fleischhauer, A., Mair, A., *et al.* (2001) Storage of Light in Atomic Vapor. *Physical Review Letters*, **86**, 783. https://doi.org/10.1103/PhysRevLett.86.783

[16] Devi, K.M., Sarkar, R., Sarma, A.K., *et al.* (2019) Exploring Polarization Independent Plasmon Induced Transparency in a Planar Terahertz Metamaterial. 2019 *IEEE Workshop on Recent Advances in Photonics* (*WRAP*), Guwahati, 13-14 December 2019, 1-3. https://doi.org/10.1109/WRAP47485.2019.9013727

[17] Cai, W., Xiao, B., Yu, J., *et al.* (2020) A Compact Graphene Metasurface Based on Electromagnetically Induced Transparency Effect. *Optics Communications*, **475**, Article ID: 126266.

[18] Zhong, M. (2020) Design and Verification of a Multiple Bands Terahertz Plasmonic Metasurface Based on Electromagnetically Induced Transparency Effect. *Optical Materials*, **106**, Article ID: 110019. https://doi.org/10.1016/j.optmat.2020.110019

[19] Dolling, G., Enkrich, C., Wegener, M., *et al.* (2006) Simultaneous Negative Phase and Group Velocity of Light in a Metasurface. *Science*, **312**, 892-894.

https://doi.org/10.1126/science.1126021

[20] Hoffman, A.J., Alekseyev, L., Howard, S.S., *et al.* (2007) Negative Refraction in Semiconductor Metamaterials. *Nature Materials*, **6**, 946-950. https://doi.org/10.1038/nmat2033

[21] Tong, S., Ren, C. and Tang, W. (2019) High-Transmission Negative Refraction in the Gradient Space-Coiling Metamaterials. *Applied Physics Letters*, **114**, Article ID: 204101. https://doi.org/10.1063/1.5100550

[22] Wong, Z.J., Wang, Y., O'Brien, K., *et al.* (2017) Optical and Acoustic Metamaterials: Superlens, Negative Refractive Index and Invisibility Cloak. *Journal of Optics*, **19**, Article ID: 084007. https://doi.org/10.1088/2040-8986/aa7a1f

[23] Ergin, T., Stenger, N., Brenner, P., *et al.* (2010) Three-Dimensional Invisibility Cloak at Optical Wavelengths. *Science*, **328**, 337-339. https://doi.org/10.1126/science.1186351

[24] Liu, Y. and Zhang, X. (2011) Metamaterials: A New Frontier of Science and Technology. *Chemical Society Reviews*, **40**, 2494-2507. https://doi.org/10.1039/c0cs00184h

[25] Yang, Y., Gao, Z., Xue, H., *et al.* (2019) Realization of a Three-Dimensional Photonic Topological Insulator. *Nature*, **565**, 622-626. https://doi.org/10.1038/s41586-018-0829-0

[26] Yan, C.H., Li, Y., Yuan, H., *et al.* (2018) Targeted Photonic Routers with Chiral Photon-Atom Interactions. *Physical Review A*, **97**, Article ID: 023821. https://doi.org/10.1103/PhysRevA.97.023821

[27] Chen, Y., Dong, L., Xu, X., *et al.* (2017) Electromagnetic Diode Based on Photonic Crystal Cavity with Embedded Highly Dispersive Meta-Interface. *Journal of Applied Physics*, **122**, Article ID: 244507. https://doi.org/10.1063/1.5010023

[28] Chen, Y., Li, Y., Zhu, K., *et al.* (2018) Nonlinear Properties of Light-Tunneling Heterostructures Embedded with a Highly Dispersive Meta-Molecule. *Optical Materials Express*, **8**, 3583-3592. https://doi.org/10.1364/OME.8.003583

[29] Liu, N., Weiss, T., Mesch, M., *et al.* (2010) Planar Metamaterial Analogue of Electromagnetically Induced Transparency for Plasmonic Sensing. *Nano Letters*, **10**, 1103-1107. https://doi.org/10.1021/nl902621d

[30] Ishikura, N., Hosoi, R., Hayakawa, R., *et al.* (2012) Photonic Crystal Tunable Slow Light Device Integrated with Multi-Heaters. *Applied Physics Letters*, **100**, Article ID: 221110. https://doi.org/10.1063/1.4724191

[31] Yao, T., Zhu, K., Chen, Y., *et al.* (2019) Meta-Interface Enhanced Light Tunneling Effect and Related Electromagnetic Diode Action. *Journal of Applied Physics*, **126**, Article ID: 165303. https://doi.org/10.1063/1.5121190

[32] He, X.J., Wang, L., Wang, J.M., *et al.* (2013) Electromagnetically Induced Transparency in Planar Complementary Metamaterial for Refractive Index Sensing Applications. *Journal of Physics D: Applied Physics*, **46**, Article ID: 365302. https://doi.org/10.1088/0022-3727/46/36/365302