

Polarization-Independent Metamaterial Sensing Based on Electromagnetically Induced Transparency

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Abstract

We propose a metamaterial structure that can achieve electromagnetically induced transparency and polarization-independent of the incident wave. The structure consists of a regular octagonal frame and four L-shaped metal wires arranged periodically. There is a strong transparent window at 4.28 GHz. Our calculation results are in good agreement with the simulation results. When changing the excitation polarization of the incident wave, the transmission spectrum remains stable. Furthermore, when we adjust the permittivity of the medium in front of the metamaterial, the frequency of the transmission valley shifts linearly with the change in permittivity. This structure can be independent of the polarization of the incident wave and has potential inspiration in fields such as sensing.

Keywords

Metamaterial, Polarization-Independent, Electromagnetically Induced Transparency, Sensing

1. Introduction

The regulation of electromagnetic waves has always been the research direction of researchers. Electromagnetically induced transparency (EIT) is a quantum interference effect [1] [2] [3] [4] [5]. When two beams of coherent light irradiate an atomic medium, at a certain frequency, a transparent window appears in the transmission spectrum [6]. It makes an otherwise opaque medium at this particular frequency transparent. Due to the strong dispersion effect of EIT, the group velocity of electromagnetic waves will be greatly reduced [7]-[12]. Furthermore, EIT can change the dispersion properties of the medium and inhibit the absorp-

tion of the medium. Therefore, EIT plays an important role in optical storage and nonlinear optical fields.

However, in the research of quantum systems, EIT has harsh requirements on the environment, such as low temperature and strong magnetism. This greatly limits the research and application of EIT. Metamaterials do not require tight control of the environment and can fine-tune individual atoms [13]. The introduction of metamaterials has greatly facilitated the study of physical systems. For example, negative refraction and invisibility cloaks [14] [15] [16] [17]. Therefore, the idea of metamaterials to construct artificial atoms to realize EIT is proposed. But most systems that achieve EIT through metamaterials require specific incident waves. When the polarization of the incident wave changes, the EIT effect weakens or disappears. This greatly limits the application of metamaterial-based EIT.

In this paper, a polarization-state-independent metamaterial is proposed to realize EIT. It consists of a regular octagonal metal frame and an L-shaped wire. Both atoms can be excited individually. When two atoms are coupled together, a transparent window emerges at frequencies that would otherwise be opaque. Our calculation results are in good agreement with the simulation results. Due to the quadruple symmetry of this structure, the transmission spectrum does not change when we change the polarization of the incident wave. In addition, when the dielectric constant of the medium in front of the metamaterial structure changes, the transparent window shifts, which provides an idea for constructing detection devices through metamaterials.

2. Structural Design

The system is composed of two structures. A regular octagon frame and four L-shaped metal lines overlap at the center. The structure is copper, etched on the substrate. The regular octagonal frame and the L-shaped metal wire can be excited by incident waves, respectively. The size of the regular octagonal metal frame has an effect on the resonant frequency. The larger the metal frame, the smaller the resonance frequency. The length of the L-shaped metal wire also affects its own resonance frequency. The longer the wire, the lower the resonance frequency. **Figure 1** shows the two artificial atoms we designed to realize the EIT. **Figure 1(a)** is a regular octagonal ring obtained by multiplying two squares with an included angle of 45° . The side length of the square is $L = 8$ mm, and the line width is 0.2 mm. It is an eightfold symmetrical figure. **Figure 1(b)** is the center of the L-shaped metal wire rotated. Line length $M = 7.6$ mm, line width 0.2 mm. is a fourfold symmetrical structure. **Figure 1(c)** is a metamaterial structure that realizes EIT-like. The regular octagonal ring is overlapped and coupled with the center of the L-shaped metal wire. The period $N = 10$ mm. The substrate is FR-4, which is a very commonly used substrate for PCB structure etching. The dielectric constant of FR-4 in CST is 4.3, and the thickness is 1.5 mm.

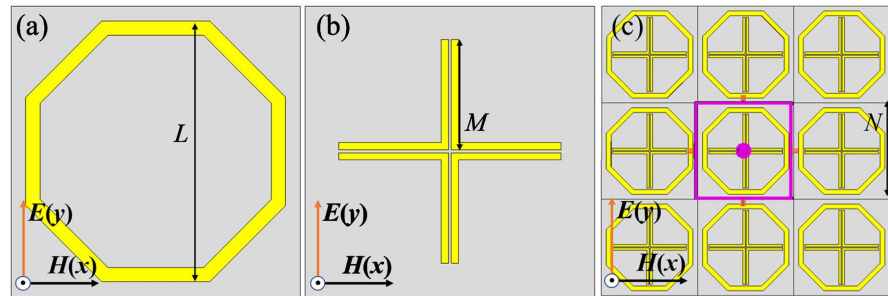


Figure 1. The structure of metamaterial diagram. (a) The regular octagon frame is obtained by overlapping two squares with side length L at an angle of 45° . (b) L-shaped metal wire, obtained by rotating the L-shaped metal wire of length M four times. (c) Periodic structure used to implement EIT. Period $N = 10$ mm.

We use CST Microwave Studio for simulation. CST microwave studio is a widely used commercial simulation software. The electromagnetic problems of any material with any structure can be calculated through the CST microwave studio. By adjusting the direction of the electric and magnetic fields of the incident wave, the polarization state of the incident wave can be changed. First, the electric field is parallel to the x-axis and the magnetic field is parallel to the y-axis. Then change the direction of the electric field and the magnetic field to change the polarization of the incident wave for simulation. In addition, we establish the coupled mode equation to calculate the transmission spectrum of the structure.

3. Simulation and Calculation Results

First, keep the direction of the electric field and magnetic field of the incident wave fixed. The electric and magnetic fields of the incident wave are shown in **Figure 1**. The transmission lines of the two structures are obtained by simulation of the regular octagonal ring and the L-shaped ring, respectively. Then couple two structures together with overlapping centers to simulation. Finally, the direction of the electric field of the incident wave was changed to simulate and observe the change of the transmission spectrum. **Figure 2** presents our simulation results for metamaterial to obtain EIT. The blue dotted line is the transmission spectrum of the regular octagon. It can be seen that there is a transmission minimum at 4.4 GHz, and the transmission coefficient is only 0.02. The L-type metal wire has a transmission minimum at 6.3 GHz, and the transmission coefficient is 0.07. When two atoms are coupled to each other, a transparent window appears at 4.28 GHz with a transmission coefficient of 0.938.

The coupled mode equation of the system can be written as:

$$\begin{aligned}\frac{d\tilde{a}_1}{dt} &= (-i\omega_1 - \Gamma_1 - \gamma_1)\tilde{a}_1 + i\kappa\tilde{a}_2 - \sqrt{\gamma_1\gamma_2}\tilde{a}_2 + i\sqrt{\gamma_1}(\tilde{s}), \\ \frac{d\tilde{a}_2}{dt} &= (-i\omega_2 - \Gamma_2 - \gamma_2)\tilde{a}_2 + i\kappa\tilde{a}_1 - \sqrt{\gamma_1\gamma_2}\tilde{a}_1 + i\sqrt{\gamma_2}(\tilde{s}).\end{aligned}\quad (1)$$

The formula for the change of transmission coefficient with parameters is:

$$t = 1 + i \left(\sqrt{\gamma_1} \widetilde{a_1} + \sqrt{\gamma_2} \widetilde{a_2} \right) / \widetilde{s}. \quad (2)$$

Through the separate simulation of the two atoms, we can obtain the specific parameters of the two atoms from blue and red lines of **Figure 2**. Here

$$\omega_1 = 4.4 \text{ GHz}, \omega_2 = 6.3 \text{ GHz}, \gamma_1 = 0.89 \text{ GHz}, \gamma_2 = 0.57 \text{ GHz}, \\ \Gamma_1 = 0.01 \text{ GHz}, \Gamma_2 = 0.024 \text{ GHz}.$$

By solving the coupled mode equation, the formula for the variation of the transmission coefficient of the metamaterial with the parameters can be obtained. **Figure 3** shows the comparison of our simulation results with the calculation results. It can be seen that our settlement results are consistent with the simulation results.

We then change the electric field polarization of the incident wave to excite

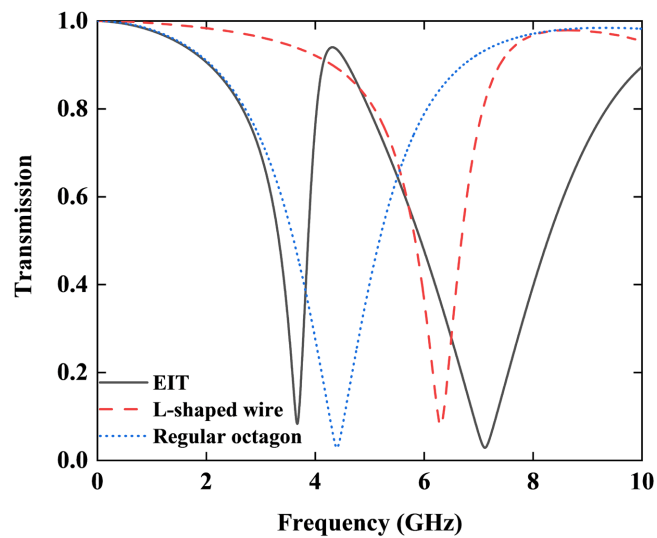


Figure 2. Simulation results of transmission spectrum of regular octagon, L-shaped metal wire and EIT.

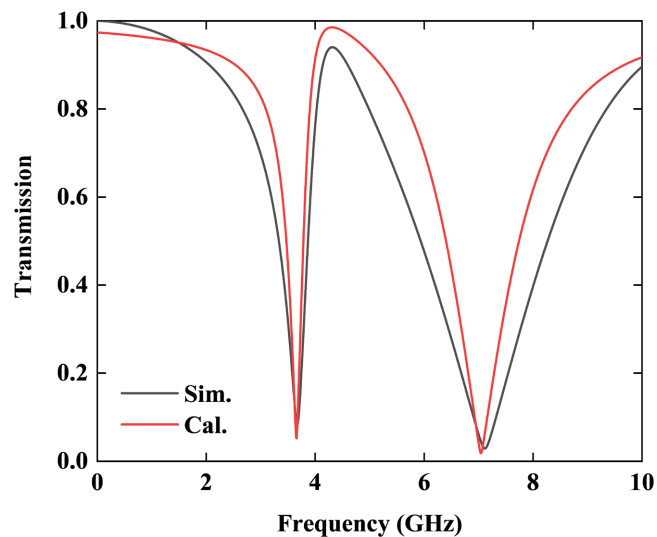


Figure 3. Comparison of calculation and simulation results.

the metamaterial. Change the direction of the electric field by adding an electric field component to the y-axis. **Figure 4** shows our simulation results. θ is the angle between the electric field vector and the positive direction of the y-axis. Since it is a quadruple symmetrical structure, it is only necessary to simulate the angle θ from 0 - 45°. It can be seen that the transmission spectrum remains stable at different θ .

According to the simulation results, it can be seen that we have realized an EIT-like that is independent of the polarization of the incident wave. The regular octagonal frame and the L-shaped metal wire are coupled with each other, so that a transparent window appears in the originally opaque transmission spectrum. The transmission spectrum solved by the coupled mode equation is consistent with the simulation results. When changing the polarization of the incident wave, the transmission spectrum remains stable.

Sensing plays an important role in many application areas. For example, human body temperature measurement, environmental humidity measurement, etc. Therefore, constructing a sensor sensitive to the change of the dielectric constant of the medium can easily detect the change of the external environment. Start by placing a dielectric plate in front of the metamaterial. Change the dielectric constant of the dielectric plate for simulation. Whether the designed structure can be used for sensing is judged by the transmission spectrum obtained by simulation.

When we place a 10 mm dielectric plate in front of the metamaterial structure. By changing the dielectric constant of the dielectric plate, the transmission spectrum can be significantly shifted. **Figure 5** shows the transmission spectrum at different dielectric constants. As the dielectric constant of the dielectric plate increases, there is a red shift in the frequency of the transmission spectrum. **Figure 6** shows the frequency of the second transmission valley in the EIT for different dielectric constants. It can be found that the variation of the detuning

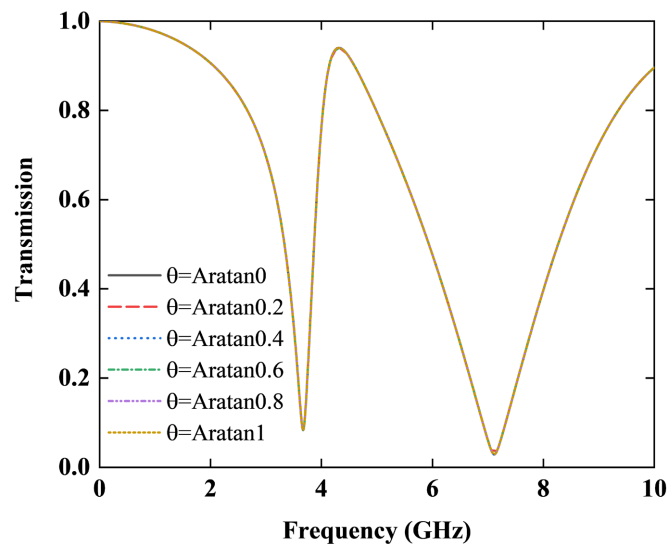


Figure 4. Transmission spectrum at different electric field directions.

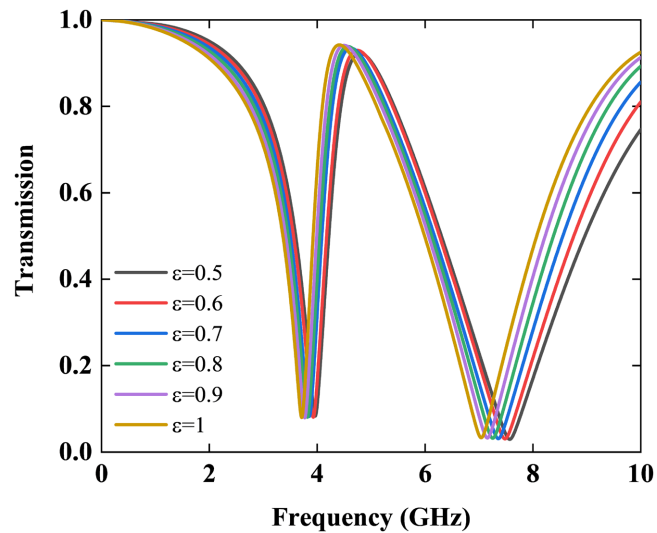


Figure 5. Transmission spectrum at different dielectric constants.

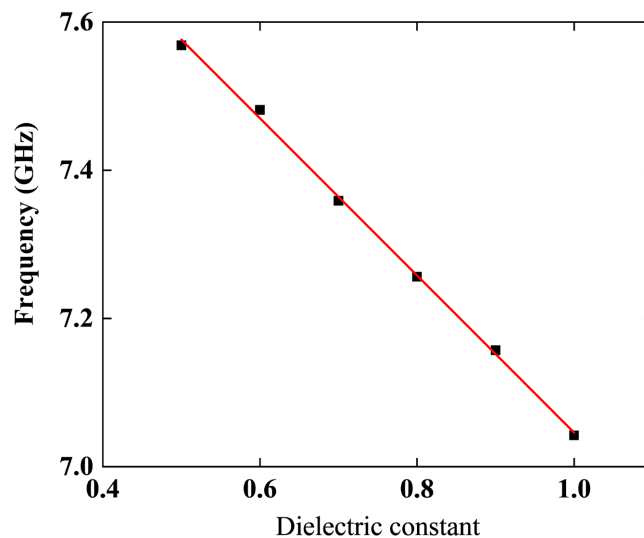


Figure 6. Fitting of dielectric constant to transmission valley.

ratio with the dielectric constant is linear in the range of the dielectric constant from 0.5 to 1.

4. Conclusion

We realize EIT-like with the polarization independence of the incident wave using metamaterials. It consists of a regular octagonal frame and a periodic arrangement of L-shaped metal wires. The simulation results show that a transparent window is obtained in the transmission spectrum at 4.28 GHz. Our coupled-mode calculation results agree with our simulation results. The transmission line remains stable for changing the polarization of the incident wave. In addition, changing the dielectric constant of the medium in front of the metamaterial causes a linear shift in the transmission lines. Our structure achieves EIT without considering the polarization of the incident wave in application and

provides an idea for EIT-based sensing.

Conflicts of Interest

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

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