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Active control scattering manipulation for realization of switchable EIT-like response metamaterial

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ABSTRACT

Electromagnetically induced transparency (EIT) is a promising technology that can improve the interaction between light and matter. The use of EIT-like in artificial functional microstructures considerably reduces the extreme requirements for the experimental observation of EIT-like spectra. In this paper, we proposed an active control electromagnetic modulator of the EIT-like spectrum induced by the metallic cut-wire metamaterial. Meanwhile, to realize switchable EIT-like behaviors, we used actively controlled scattering spectral modulation to create "on/off" states and the specific operation is to rotate the "Y" shape symmetry metallic cut-wire metamaterial counterclockwise with a 30° step. We performed numerical calculations and detailed analyzes of the microscopic response of the metamaterial and showed the mode coupling between the electrical dipole resonances. Meanwhile, we have confirmed that the switching properties of the EIT-like spectrum can be significantly modulated under rather a small rotation angle at the transmission characteristic peak of the metamaterial and that the EIT-like resonance frequency modulation based on actively controlled scattering operation shows the advantages of extended metamaterial resonance modulation and operating frequency bands.

1. Introduction

In recent years, the theory and application of metamaterials have developed into a new research hotspots due to their easy-to-use electromagnetic properties [1–3], and metamaterials are widely used in various functional devices, such as resonators [4], wave guide modulators [5], filters [6], biochemical sensors [7] and optical switching devices [8]. Compared to natural materials, metamaterials can effectively adapt their response to external stimuli by modeling the geometry and the local resonance behavior of the individual materials. Meanwhile, researchers can analogize how natural atoms respond to external stimuli to mimic the building blocks of metamaterials, also known as meta-atoms [9,10]. Electromagnetically induced transparency effect [11,12] is one of the typical phenomena.

Electromagnetically induced transparency (EIT) is a coherent process in atomic physics. This is based on the observation of quantum interference between different excitation paths from the ground state to the final state in an atomic system with three states and leads to a narrow transparent window [13]. The sharp scattering of EIT causes slow light and increases the interaction between light and matter [14]. However, the extreme environment required for the quantum EIT phenomenon makes it impossible for practical applications. Particularly, realization of the EIT-like effect was usually achieved by using two kinds of schemes: the bright–dark mode coupling [15] and the bright–bright mode coupling [16]. Metamaterials provide a novel platform to easily implement classic analogues of quantum EIT behavior. A plasmonic EIT in planar metamaterial were firstly proposed based on the near-field coupling between bright and dark modes [11]. Subsequently, with the rapid development of metamaterials [17,18], the two-dimensional metamaterials and artificial functional microstructures instead of extreme environments were used to simulate EIT-like

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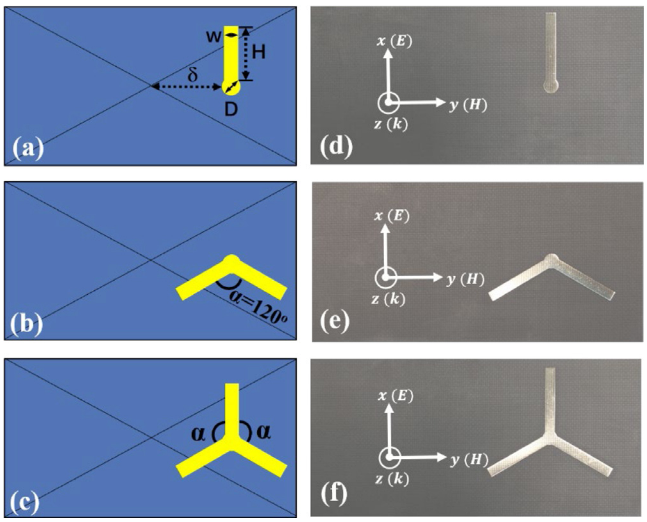

Fig. 1. (a), (b) and (c) Schematic and (d), (e) and (f) photograph of the metallic cut-wire metamaterial.

behavior [1,19–21]. However, conventional metamaterials normally stimulate the EIT-like effect in a narrow operating frequency band, which often severely limits the practical application of metamaterials in EIT-like analogues. In order to improve the performance, some active constituents offer a potential solution for the EIT-like application restrictions, for examples active elements [22], graphene [23,24], phase change materials [25,26], semiconductor materials [27], liquid metals [14] and phase modulation [28], which are these schemes that have been proposed in the past few years to achieve versatile switchable EIT-like and active control EIT-like behavior. Recently, Zhang et al. [14]. showed that the liquid metal-based metamaterial is composed of a copper wire pair and a tiny pipe filled with a liquid metal, namely eutectic gallium–indium to realize the switchable EIT-like. However, most of the EIT-like switches mentioned above are only simulation work [29,30], only few of them have been experimentally implemented and showed limited application.

In this article, we propose and experimentally verify a switchable EIT-like response metamaterial, which consists of three electrical dipole units for metallic cut-wire. Meanwhile, to realize switchable EIT-like behaviors, we use actively controlled scattering spectral modulation to create "on/off" states in which the active control behavior is achieved by mechanically rotating the metamaterial structure and the specific operation is to rotate the "Y" shape symmetry metallic cut-wire metamaterial counterclockwise with a 30° step. Simulated and experimental results both show that the transparency peak and switchable state could be realized under normal incidence. We have found that when a broken structural symmetry is introduced in metamaterials, switchable EIT-like behavior can occur due to destructive or constructive interference between electrical dipole modes. Numerical calculations and detailed analysis of the microscopic response metamaterials are used to illustrate the mode coupling between electrical dipole resonators. Our results will likely result in a practical application based on the electromagnetically induced transparency of the electrically control.

2. Design and simulation

Fig. 1(a), (b) and (c) displays the schematic of the metallic cut-wire metamaterial of the bright–dark mode and coupling mode, which is composed of vertical cut-wire as a dark mode resonator, a horizontal inverted "V" shaped cut-wire as a bright resonator and a "Y" shape symmetry metallic cut-wire metamaterial as a coupled resonator, respectively. The metal cut-wire pattern is made of copper and has a conductivity of 5.8×10^{7} S/m and a depth of 0.035 mm. The 72.14 mm $\times$ 34.04 mm $\times$ 1.0 mm substrate is Teflon, its relative permittivity is 2.65 and the loss tangent is 4×10^{-4}. The geometrical parameters of the cut-wire metamaterial are as follows: $H = 13.48$ mm, $w = 2$ mm, $D = 3$ mm, $\delta = 14.5$ mm and $\alpha = 120°$. The metamaterial structure shown in Fig. 1(b) is composed of two cut-wire metamaterial structures in Fig. 1(a) which rotates 120° clockwise and counterclockwise with the center of the circle with diameter D, respectively. The photograph of the fabricated sample is shown in Fig. 1(d), (e) and (f). Metal cut-wire metamaterials are made using standard circuit board (PCB) technology, which is then inserted into a standard rectangular waveguide from WR284 [31] to measure the scattering parameters of the metamaterial. The mode of the polarized electric field that perpendicularly falls on the metamaterial along the vertical cut-wire is the TE_{10} mode and the corresponding parameters are recorded using a vector network analyzer (Advantest R3767CH; Advantest, Tokyo, Japan).

The commercial simulation software CST Microwave Studio2019® was used to numerically characterize the designed spectral response of the metamaterial coupling and the EIT-like effect. From Fig. 2(a) we can see that the metamaterial of the vertical cut-wire is excited neither by the incident wave nor by the radiation coupled to the far field. It is therefore regarded as a dark mode resonator, whose transmission spectrum (black curve) is close to a constant value (dB). In the waveguide, the horizontal inverted "V" shaped cut-wire metamaterial couples strongly to the incident TE_{10} mode and is therefore a bright resonator, we can see that there is a resonance peak in the transmission spectrum at approximately 3.50 GHz (red curve). It should be noted that when two kinds of metamaterials with different structures are combined into the "Y" shape symmetry metallic cut-wire metamaterial the transmission spectrum is a blue curve. The Fig. 2(b) can be seen that in a "Y" shaped symmetrical metal cut-wire metamaterial, the interference between the light mode and the dark mode is similar to the interference between two different excitation paths from the ground state to the final state in a three energy levels EIT system. Two possible excitation paths include $|0\rangle$-$|1\rangle$ and $|0\rangle$-$|1\rangle$-$|2\rangle$-$|1\rangle$ [21], which correspond to excitation by the electric wave of the incident wave and the horizontal and vertical cut-wire, respectively.

3. Results and discussions

In order to observe the interaction between the two parts of the metamaterial structure and to clearly analyze the functional principle similar to the EIT-like phenomenon, we obtained its electric field distribution by calculation in CST Microwave Studio, as shown in Fig. 3. The electrical dipole response of an alone horizontal inverted "V" shaped cut-wire is much stronger than the electrical dipole response of an alone vertical cut-wire. At the same time, due to the destructive interference between the light mode and the dark mode, the electrical dipole scatter of the vertical cut-wire is strongly suppressed. As a result, destructive interference between the two resonance modes leads to the observed occurrence of the EIT-like phenomenon [32,33].

The simulated transmission spectra of the bright mode, dark mode, and coupled mode metamaterials are verified by experiments. Samples with the same geometric dimensions and the same material parameters as the simulation are made, as shown in Fig. 4(a). The metamaterial sample was embedded in a standard rectangular waveguide (WR-284) and the transmission coefficient of the sample was measured through two ports device connected to the waveguide using a vector network analyzer (as shown in Fig. 4(b)). The measured transmission spectrum of the proposed metamaterial, namely the vertical metallic cut-wire (black curve), the horizontal metallic inverted "V" shaped cut-wire (red curve) and the hybrid "Y" shaped symmetrical metallic cut-wire structure (blue curve) are shown separately in Fig. 4(c). Obviously, we have shown the EIT-like spectral phenomenon, which can produce a hybrid "Y" shaped symmetrical cut-wire metamaterial from a vertical cut-wire and a horizontal inverted "V" shaped cut-wire. The transmission spectra of the experimental measurements are in good agreement

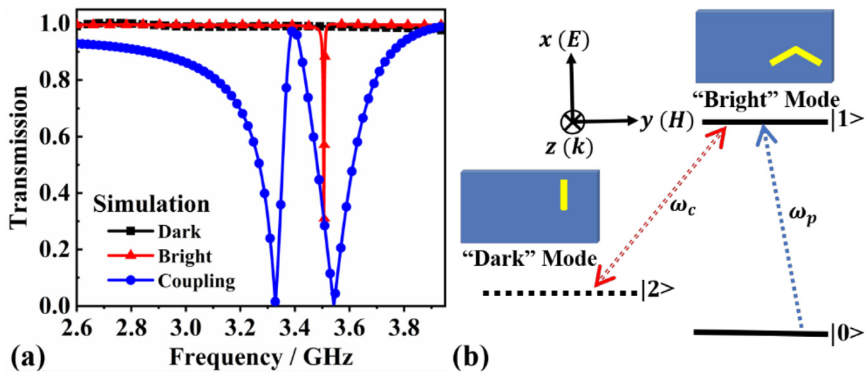

Fig. 2. (a) The transmission spectra of the vertical cut-wire (black curve), the inverted "V" shaped horizontal cut-wire (red curve) and the "Y" shaped symmetrical metal cut-wire (blue curve) were simulated, respectively. (b) Schematic diagram of coherent interference between bright and dark modes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

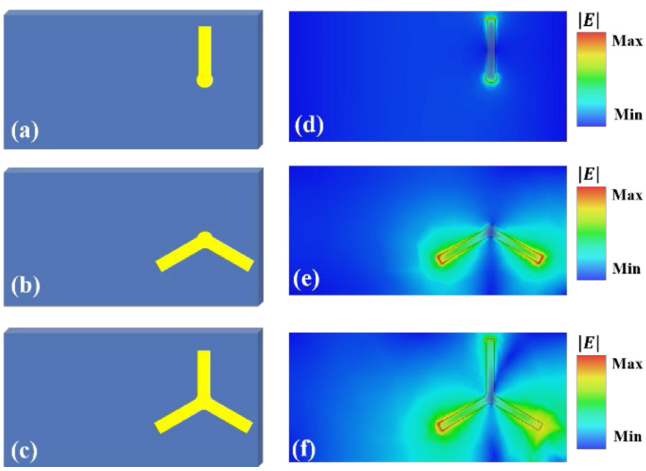

Fig. 3. Schematic of the different metallic cut-wire metamaterial (a) (b) and (c), Electric field distribution of various metallic cut-wire metamaterials (d), (e) and (f).

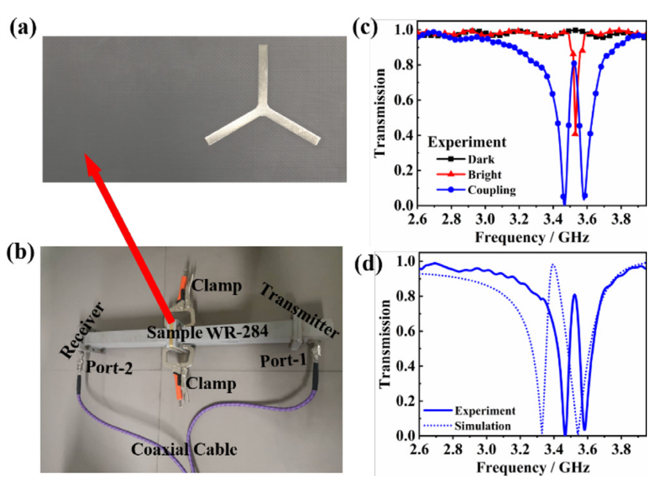

Fig. 4. (a) Photograph of the "Y" shape symmetry metallic cut-wire fabricated sample. (b) The measurement setup. (c) Measured transmission spectra for the metamaterials, vertical metallic cut-wire (black curve), horizontal inverted "V" shaped cut-wire (red curve) and "Y" shape symmetry metallic cut-wire (blue curve). (d) Comparison the simulated and experimental transmission spectra of "Y" shape symmetry metallic cut-wire. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with our numerical simulation predictions. In Fig. 4(d), the simulated (dotted line) and experimental (solid line) transmission spectra are compared. The transmission peak measured experimentally has a weak overall blue shift, which might be caused by the parameter errors, such as permittivity and dimensions, used in simulations.

The EIT-like phenomenon can clearly be observed in Fig. 5(a) when the "Y" shape symmetry cut-wire structure metamaterial is located at 0°. First, the EIT-like effect disappears when the metamaterial of the "Y" shape symmetry cut-wire structure is rotated 30° counterclockwise, mainly attributable to the fact that the electrical dipole scattering of the cut-wire in the horizontal direction is not strongly suppressed, so that constructive interference occurs between the light mode and the dark mode. Subsequently, when the "Y" shape symmetry cut-wire structure metamaterial rotated 60°, the EIT-like phenomenon will occur at about 3.53 GHz, which demonstrate that the electric dipole response of the inverted "V" shaped horizontal cut-wire alone is much stronger than that of the vertical cut-wire alone, but the opposite is true when the metamaterial of the "Y" shaped symmetric cut-wire structure is rotated 30° counterclockwise. This is mainly due to the presence of destructive interference between the light mode and the dark mode, which strongly suppresses the electrical dipole scatter of the vertical cut-wire. In other words, this confirms the destructive interference between the electric dipole modes of the orthogonal electric dipole resonator. Next, when the metamaterial of the "Y" shape symmetry cut-wire structure is rotated to a direction of 90°, the electromagnetic EIT-like phenomenon disappears. Finally, when the metamaterial of the "Y" shape symmetry cut-wire structure was rotated to 120°, the EIT-like phenomenon appeared again. In the whole cycle T, where $T = 120°$, three EIT-like phenomena occurred and two EIT-like phenomena disappeared. Analogy to a switch, in one cycle T, three "on" states and two "off" states appear [34]. Meanwhile, we experimentally verified the switchable EIT-like response that appeared within a period T (turned counterclockwise 120°), as shown in Fig. 5(b). When the metamaterial of the "Y" shaped symmetrical cut-wire structure is rotated for a period T, an EIT-like effect similar to the simulation result also appears. However, the transmission peak measured experimentally has a weak overall blue shift, which is mainly because the dielectric constant of the dielectric substrate used in the experiment and the dielectric constant used in the simulation are not exactly the same.

Finally, as shown in Fig. 6, when the anisotropic "Y" shape symmetry metallic cut-wire metamaterial rotates for one period ($T = 120°$), we can find that different transmission spectra can produce different electric field distributions through numerical simulation. It is worth noting that when the rotation angles are 0°, 60°, and 120°, we can observe the appearance of EIT-like behavior in Fig. 6(b), and when the rotation angles are 30° and 90°, we can also observe that there is no EIT-like phenomenon in Fig. 6(c). The main reason for the above two different phenomena is that the incident electromagnetic wave is a linearly polarized TE_{10} mode. The metamaterial of the left–right symmetrical "Y" shape symmetry metallic cut-wire will produce

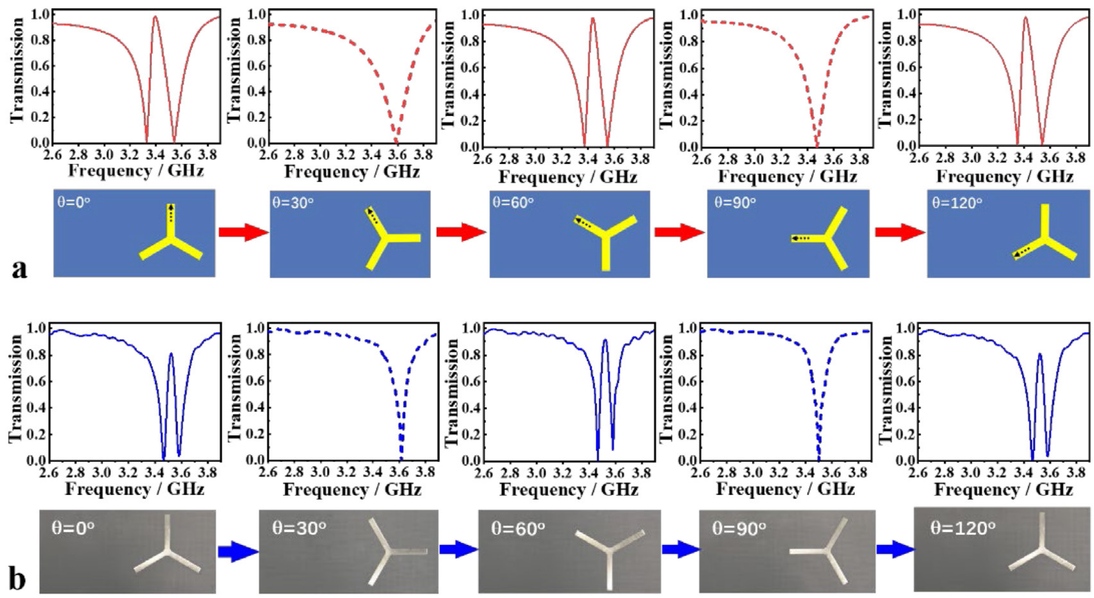

Fig. 5. (a) Simulated transmission spectrum of "Y" shape symmetry metallic cut-wire at different rotation angles. (b) Experimental transmission spectrum at different rotation angles.

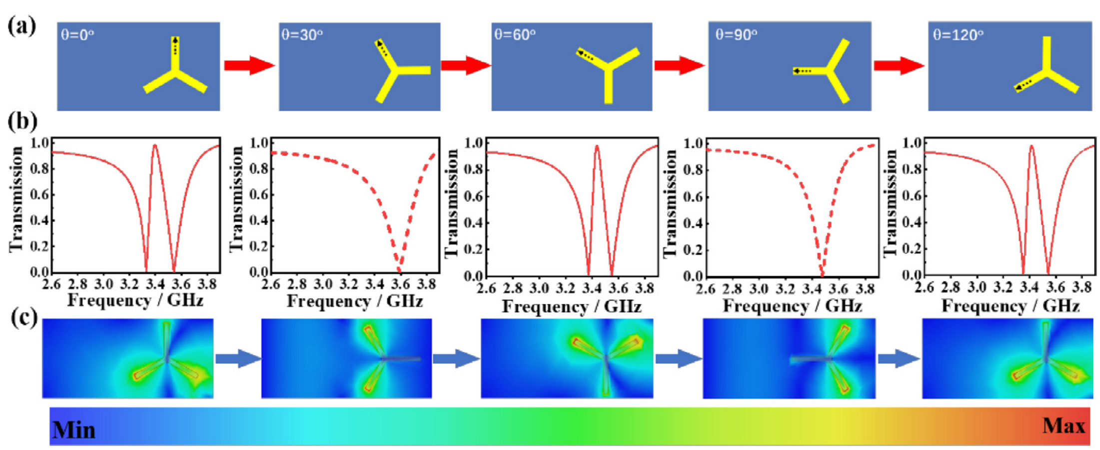

Fig. 6. (a) The "Y" shape symmetry metallic cut-wire structure rotates 120° counterclockwise with the step length of 30°, (b) Transmission spectrum at different angles, (c) Electric field distribution at different angles.

an "on" state, and the metamaterial of the vertically symmetric "Y" shape symmetry metallic cut-wire will produce an "off" state. To show more details on the switchable EIT-like response metamaterial, we numerically simulated the electric field distribution of the "Y" shape symmetry metallic cut-wire metamaterial in the "on/off" state at different rotation angles in Fig. 6(c). From the electric field distribution diagram, we can find that when the rotation angles are 0°, 60°, and 120°, the three center-symmetric metallic cut-wire of the "Y" shape symmetry metallic cut-wire metamaterial all generate strong electric fields, making the destructive interference occurs between bright mode and dark mode, so destructive interference between the two resonance modes results in the observed EIT-like phenomenon. When the rotation angles are 30° and 90°, the electric field of the horizontal cut-wire of the "Y" shape symmetry metallic cut-wire metamaterial is very weak, which causes constructive interference between the light mode and the dark mode, and finally in the resonance mode no EIT-like phenomenon was observed [35,36]. Therefore, we can also explain why different "on/off" states occur in the entire period T through the electric field distribution in different states.

4. Conclusion

In conclusion, we propose and experimentally verify that a metamaterial made from three symmetrical metal cut-wire structures can achieve a switchable EIT-like response by rotating it counterclockwise. We observed EIT-like phenomenon are caused by the coherent interference of the "Y" shape symmetry metallic cut-wire metamaterial which is made of a vertical cut-wire and a horizontal inverted "V" shaped cut-wire. We demonstrated that a new state of the EIT-like phenomenon occurs every time when the "Y" shape symmetry metallic cut-wire metamaterial structure is tuned or switched by 30° with a period of $T = 120°$. The experimental principle confirms that the switching transmission of the metamaterial can be significantly modulated at a relatively small angle of rotation similar to the characteristic peak of the EIT-like spectrum. Meanwhile, the resonant frequency modulating based on active control scattering manipulation EIT-like has benefits for extending the working band of metamaterial based resonant modulators.

CRediT authorship contribution statement

Chao Du: Helped with the simulation, Data analyses, Writing - original draft. **Di Zhou:** Conception of the study, Data analyses, Writing - original draft. **Huan-Huan Guo:** Helped with the simulation. **Yong-Qiang Pang:** Helped with the simulation. **Hong-Yu Shi:** Helped with the simulation. **Wen-Feng Liu:** Analysis with constructive discussions. **Charanjeet Singh:** Analysis with constructive discussions. **Sergei Trukhanov:** Revised the paper. **Alex Trukhanov:** Revised the paper. **Zhuo Xu:** Conception of the study.

Declaration of competing interest

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.

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