Ultra-Broadband Electromagnetically induced Transparency in Metamaterial Based on Conductive Coupling

Tiantian Zheng (zhengtiantian1108@163.com)
Shanghai University
Zhongyin Xiao
Shanghai University https://orcid.org/0000-0001-9703-030X
Mingming Chen
Shanghai University
Xiang Miao
Shanghai University
Xiaoyu Wang
Shanghai University

Research Article

Keywords: electromagnetically induced transparency, metamaterials, broadband, conductive coupling

Posted Date: August 10th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-777775/v1

Version of Record: A version of this preprint was published at Plasmonics on November 15th, 2021. See the published version at https://doi.org/10.1007/s11468-021-01561-z.

Ultra-Broadband Electromagnetically induced Transparency in Metamaterial Based on Conductive Coupling

Tiantian Zheng[1,2] , Zhongyin Xiao[1,2,*] ,Mingming Chen[1,2], Xiang Miao[1,2], Xiaoyu Wang[1,2]

*Corresponding author:zhyxiao2shu.edu.cn

1 School of Communication and Information Engineering, Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Shanghai University, Shanghai, China

2 School of Communication and Information Engineering, Shanghai Institute for Advanced Communication and Data Science, Shanghai University, Shanghai, China

Abstract: In this paper, a structure comprising a horizontal metal strip resonator(SR) and four C-shape ring resonators(CRRs) is proposed, obtaining a broadband electromagnetically induced transparency-like(EIT-like) effect. The SR and CRRs are classified into bright mode and dark mode depending on whether they can be directly excited by the incident electromagnetic wave. The three-level Λ -type system and electric field are used to explain the mechanism of EIT-like effect. Meanwhile, by decreasing the distance between SR and CRRs, a transparency window of 1.4THz with relative bandwidth of 91.93% is observed. It is found that when the bright and dark mode are directly contacted, the EIT window increases rapidly via conductive coupling, which can be explained by the surface current. Our work provides a new method for wide band EIT-like effect, which has certain value in the field of slow light, filter and non-linear optics.

Keywords electromagnetically induced transparency · metamaterials · broadband · conductive coupling

Introduction

EIT is a phenomenon of quantum interference in a three-level system, which can weaken the absorption at the resonance frequency, resulting in a sharp transparency window[1]. During the generation process of EIT, the atomic medium is usually accompanied by a strong dispersion effect, which will greatly reduce the optical speed, so as to realize many important applications, such as slow light propagation[2], optical filters[3] and optical storage[4]. Nevertheless, the conditions of EIT effect in atomic system are too harsh to achieve in the practical environment, often requiring ultra-low temperature and high intensity laser. With the development of metamaterials, EIT based on metamaterials has attracted extensive attention from scholars[5]. In metamaterials, bright-dark mode or bright-bright mode coupling is commonly used to form EIT without strict environmental conditions[6,7]. With the deepening of the research on EIT metamaterials, it is found that there are still many shortcomings in the EIT-like effect, such as narrow band and sensitive polarization direction[8].

Since EIT is generated by the interference of bright and dark modes, its bandwidth is always very narrow due to this limitation, which greatly limits the practical application. Wu et al. first realized broadband slow light using a 41-layer design based on a double-continum fano resonance[9]. However, it is difficult to fabricate. Later, Liu et al. demonstrated a back-to-back self-asymmetric split-ring resonator in Dirac semimetal metamaterials observing tuneable broadband transparency window [10].

Zhu et al. proposed a scheme of broadband EIT-like effect based on Mie resonances in all-dielectric microstructure [11]. Nevertheless, its bandwidth is not broad enough. Zang et al. presented a structure with 14 dark modes obtaining a wide transparency window based on hybridization gap [12]. This structure is a bit complicated.

Most of the current structures are too complex, or the relative bandwidth is not very wide. In this paper, a structure with a bright mode and four dark modes is proposed to obtain broadband EIT-like effect at terahertz region. The planar design is simple but realizes a bandwidth of 91.93% at 3 dB transmission. The EIT cell consists of a horizontal metal strip resonator (SR) and four C-shape ring resonators (CRRs). With the increasing number of dark modes, the transparent window expands gradually. Subsequently, the coupling distance between bright and dark modes is adjusted, broadening the transparency window. The proposed structure with obvious slow light effect can achieve wide EIT effect, which is of great significance to design metamaterial filter, slow light devices and broadband polarization devices.

Structure

Figure 1(a) illustrates a unit cell of the proposed EIT-like metamaterial, which consists of a horizontal bar and four C-shape ring resonators made by gold. The dielectric material is quartz with a thickness of 30 μm.Fig. 1(a) shows the planar geometry of the proposed EIT-like metamaterial. The thickness of gold is 5 μm.The geometric parameters of this design are as follows: P_x=114 μm, P_y=134μm, L=80μm, r=31μm, g=40μm, w=4μm and d=10μm. The incident wave propagates along the z-axis, which is perpendicular to the quartz substrate. The commercial tool CST Microwave Studio is used to simulate this proposed structure.

To understand the mechanism of EIT effect, a quantum three-level Λ-type system is used[13]. This system is comprised of a ground state $|0\rangle$ and two upper states $|1\rangle$ and $|2\rangle$ as shown in the Fig.1(b). When the electromagnetic waves with x-axis polarization propagate, the metal bar is excited strongly, producing a resonance. The resonance frequency is ω_1,the damping rate is γ_1. The SR acts as a bright mode here and the excitation path is $|0\rangle \to |1\rangle$. The CRRs don't respond directly to incident waves, thus the path $|0\rangle \to |2\rangle$ is forbidden. The CRRs is dark mode, which is characterized by the transition frequency ω_2 and a damping rate γ_2. The CRRs couple with SR, generating a new path $|0\rangle \to |1\rangle \to |2\rangle \to |1\rangle$. Destructive interference between two excitation paths produces EIT effect.

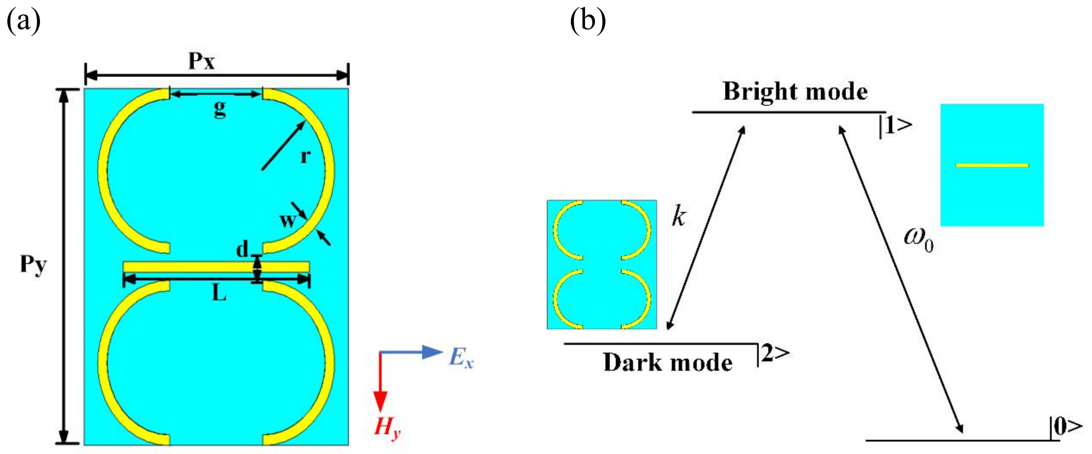

Fig.1(a) The planar geometry of the proposed EIT-like metamaterials and (b)level scheme for EIT in a three-level atom system.

Results and discussions

The simulation results of sole SR, CRR and complete structure are shown in Figure 2. When the electromagnetic wave is incident to the structure, the SR generates a resonance at 1.1168 THz, thus SR is bright mode. The response of CRR to incident electromagnetic wave is almost a straight line, which is not excited by incident electromagnetic waves and works as dark mode[14]. The blue line in the figure represents the relationship between the transmittance and the frequency of the complete structure. There are two dips at 0.8544 THz and 1.4704 THz, and the bandwidth of the transparency window is 0.616 THz. At this time, a wide EIT phenomenon appears at the resonance of 1.1992 THz, extending from 0.9037 to 1.4087 THz at 3 dB transmission.

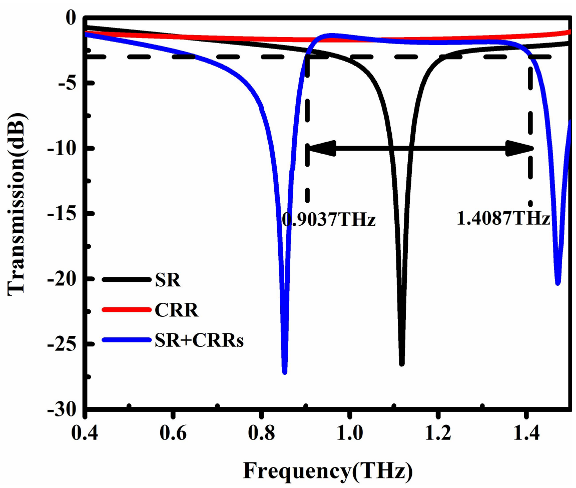

Fig.2 The transmission curve of the sole SR, CRRs and proposed EIT-like metamaterials

To get a wider EIT, we can start by reducing the loss of EIT or enhancing the coupling between bright and dark modes[15,16]. The loss of EIT consists of ohmic loss and radiation loss. On the one hand, take gold with higher conductivity to reduce the ohmic loss. On the other hand, increase the number of dark mode to reduce radiation loss[17].By increasing the number of dark mode resonators, the loss coefficient can be reduced, and the coupling coefficient between the light and dark modes can be increased, so as to expand the bandwidth. As shown in Fig.3, the EIT bandwidth expands as the number of dark mode resonators increases.

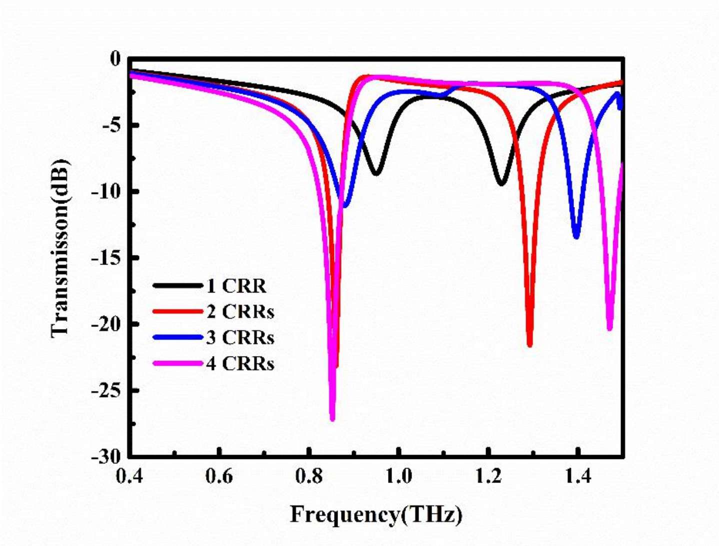

Fig.3 The transmission curves of different dark modes.

Moreover, the interference phenomenon are interpreted by the two particle model quantitatively[18,19].

$$\begin{aligned} &\ddot{x}_1(t)+\gamma_1\dot{x}_1(t)+\omega_0^2 x_1(t)+k^2 x_2(t)=qE_0 \\ &\ddot{x}_2(t)+\gamma_2\dot{x}_2(t)+(\omega_0+\Delta)^2 x_2(t)+k^2 x_1(t)=0 \end{aligned} \tag{1}$$

Here, particle 1 and 2 represent bright mode and dark mode, respectively. x_1, x_2 represent the transmission amplitude of bright mode SR and dark mode CRRs. γ_1 and γ_2 represent the damping rates of two particles. ω_0 and $\omega_0+\Delta$ represent the resonance frequency of the bright mode and the dark mode. k is the coupling strength between bright mode and dark mode. q is the coupling strength of bright mode with the incident wave.

Solving the equation (1), the effective susceptibility X_{eff} is obtained[11].

$$\mathrm{X}_{eff}=\frac{q^2}{\varepsilon_0}\cdot\frac{\left[\omega^2-(\omega_0+\Delta)^2+i\gamma_2\omega\right]}{k^4-\left[\omega^2-(\omega_0+\Delta)^2+i\gamma_2\omega\right](\omega^2-\omega_0^2+i\gamma_1\omega)} \tag{2}$$

Therefore, we obtain the transmission of electromagnetic waves through structures:

$$|\mathrm{T}|=\left|(4\sqrt{\mathrm{X}_{eff}+1})\Big/\left(\left(\left(\sqrt{\mathrm{X}_{eff}+1}+1\right)^2\right)\right)e^{j\frac{2\pi d}{\lambda_0}\sqrt{\mathrm{X}_{eff}+1}}-\left(\sqrt{\mathrm{X}_{eff}+1}-1\right)^2 e^{-j\frac{2\pi d}{\lambda_0}\sqrt{\mathrm{X}_{eff}+1}}\right| \tag{3}$$

Where d is the thickness of the planar structure and λ_0 is the wavelength in a vacuum. Through the above calculation, we can obtain the calculated transmission curve as shown in Fig.4, which is consistent with simulated transmission spectrum.

(a) (b)

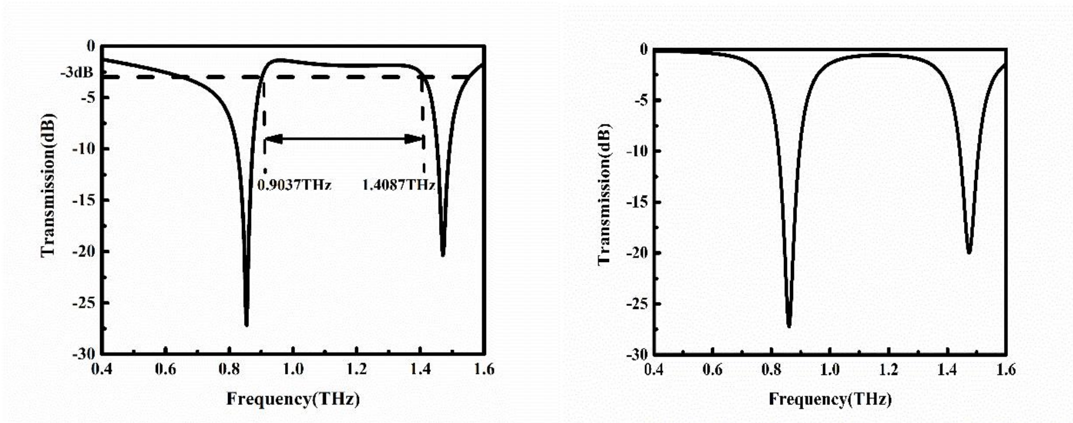

Fig.4. (a)The simulated transmission spectrum of proposed structure. (b)The calculated transmission spectrum of proposed structure.

In order to further illustrate the mechanism of the EIT-like effect, Fig.5.(a)-(c) presents the electric field of the sole SR, sole C-shape resonator and the whole structure, respectively. Fig.5.(a) indicates that the SR is strongly excited by the incident waves, and the electric field distributed in the both ends of the SR at 1.1168THz is very strong, which is a typical dipolar localized surface plasmon(LSP) resonance phenomenon. However, the electric field of CRRs is very weak as shown in the Fig.5(b). Fig.5(c) depicts the electric field of the entire structure at the the resonance frequency, the CRRs are excited by the near-field couplings with SR. The strong excitation of CRRs (dark mode) can suppress the reflection and absorption of SR (bright mode) in a destructive interference way [20], therefore, an EIT-like effect is observed.

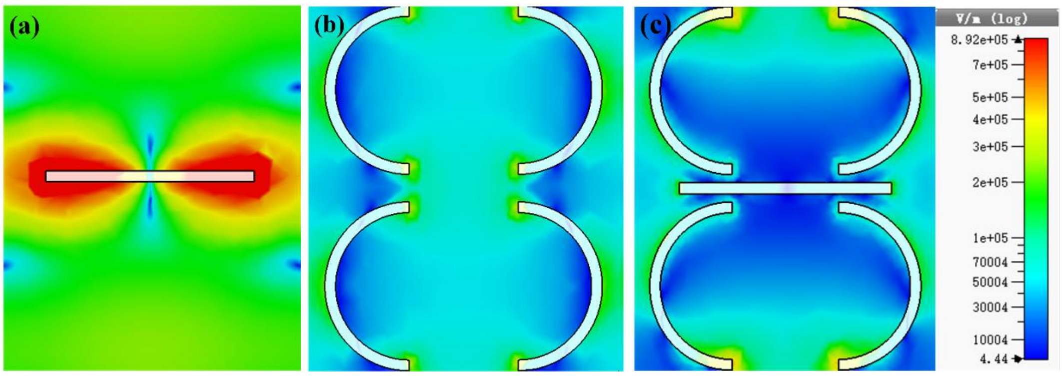

Fig.5. (a), (b) and (c) are electric fields of sole SR (at 1.1168THz) , sole C-shape resonator(at 1.1168THz) and the whole structure(at the resonance of 1.1992THz), respectively.

Then, we can get better coupling effect by reducing the coupling distance d to obtain greater broadband effect. As d gradually decreases, dip 1 on the left has a slight red shift. Intriguingly, when d changes from 5μm to 4μm, the bandwidth suddenly increases greatly and a wider EIT is obtained, as shown in the Fig.5(a). The full width of the transparency region reaches up to 1.0768THz. We define the bandwidth $\Delta f = f_H - f_L$,center frequency $f_0 = (f_H + f_L)/2$, relative bandwidth $f_{foc} = \Delta f / f_0$ at 3dB is about 91.93%. In order to prove the correctness of the transmission spectra when the distance d equals to 4, the calculated transmission spectra of proposed structure is given in the Fig.6(b). It can be seen from Figs.6 (a) and (b) that the calculated curves are roughly consistent with the simulated curves, and the frequencies at the two dips are in good agreement.

(a) (b)

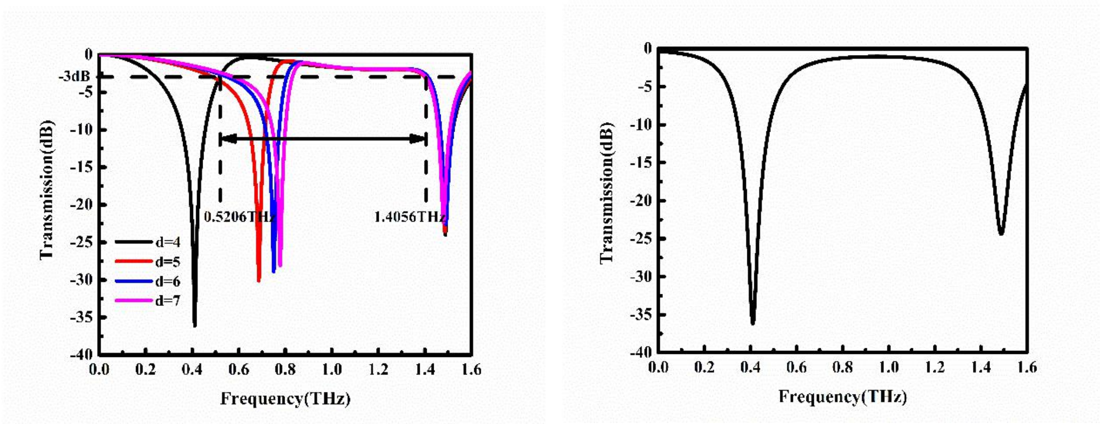

Fig.6. (a)The simulated transmission spectrum of different coupling distance. (b)The calculated transmission spectrum of proposed structure (d=4).

The reason for the unique property is that when d decreases to 4, the distance between the bright and dark mode approaches zero, hence there is direct contact between them. If there is metal connection between the resonators, it is possible to transfer energy by connecting the metal[21]. There are not only magnetic field coupling and electric field coupling between bright resonator and dark resonator, but also conductive coupling of conduction energy through metal structure. These couplings make the whole structure produce EIT phenomenon and enhance EIT phenomenon due to conductive coupling. As shown in the Fig.6, the expansion of bandwidth is due to the left shift of the first dip. To elucidate the the mechanism of the conductive coupling, the surface current of the first dip without contact (d = 10) and the one with contact (d = 4) are shown in Fig. 7.

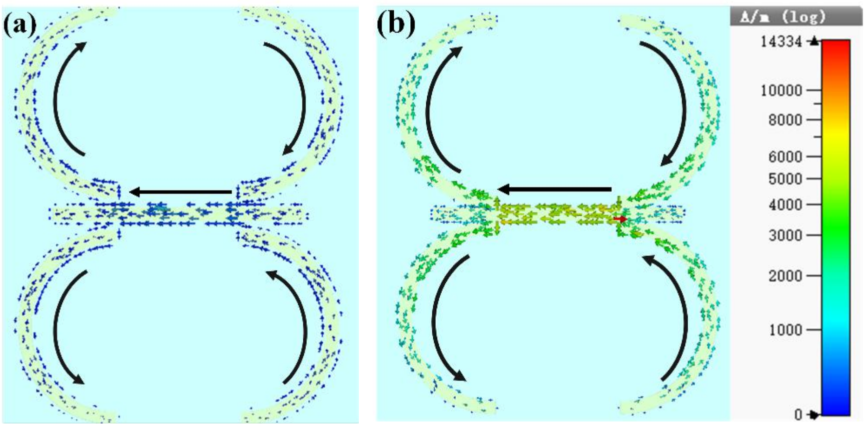

Fig.7 (a)Surface currents of the proposed EIT-like structure without contact(d=10) and (b)with contact(d=4)

Comparing Fig.7(a) and Fig.7(b), although the frequencies of the two dips of the two structures and the surface currents are different, the characteristics of the current distribution are the same. The currents in the SR and CRRs flow in phase. For Fig.7(b), due to the connection of the bright and dark resonators, the current superposition in the same direction increases significantly in the bright mode, and is greater than the current of the bright mode without connection. At this time, the current of the bright and dark modes is connected, and the energy between them can also be coupled through this current, which is larger than that through capacitance coupling. Therefore, the conductive coupling makes the EIT greatly enhanced simultaneously.

We compare the performance of this broadband electromagnetically induced transparency with other EIT-like phenomenon in the terahertz regime. As shown in table 1, we can see that our broadband electromagnetically induced transparency has greater bandwidth.

Table 1 Comparison with Other Broadband EIT-like effect

	Transparency region	Width of the transparency region
Ref.10	0.47THz~0.67THz	0.2THz
Ref.11	1.086THz~1.44THz	0.354THz
Ref.15	1.05THz~1.46THz	0.41THz
Ref.17	0.75THz~1.27THz	0.52THz
This paper	0.4112THz~1.488THz	1.0768THz

Conclusions

In this paper, a broadband EIT structure is proposed, which consists of a transverse metal strip and four C-shape resonators arranged up and down the metal strip. The three-level system and electric field explain the physical mechanism of the proposed EIT-like metamaterial. By increasing the number of dark mode and reducing the coupling distance between the bright and dark mode, a transparent window with relative bandwidth of 91.93% is observed. It is found that after the direct contact between the bright mode and dark mode, the EIT phenomenon has been greatly broadened, which is explained by the surface current mechanism. Our work has potential applications in metamaterial slow light, broadband filters and sensors.

Declarations

Funding: This study is supported by the National Natural Science Foundation of China (Grant No.61275070) and Natural Science Foundation of Shanghai (Grant No. 15ZR1415900).

Competing Interests: The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Availability of data and materials: All data generated or analyzed during this study are included in this published article.

Author contributions

Tiantian Zheng: Conceptualization, Methodology, Software, Writing-Original Draft, Writing-

Review& Editing. **Zhongyin Xiao:** Validation, Writing - Review & Editing, Supervision. **Mingming Chen:** Software, Data Curation. **Xiang Miao:** Software, Formal analysis. **Xiaoyu Wang:** Investigation, Supervision.

Consent for publication: Written informed consent for publication was obtained from all participants.

Consent to Participate: Written informed consent for participate was obtained from all participants.

Ethics approval: We declare that this article is original, has not been published before, and is not currently considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

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