The metamaterial analogue of electromagnetically induced transparency by dual-mode excitation of a symmetric resonator*

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Electromagnetically induced transparency (EIT) is obtained in a symmetric U-shaped metamaterial, which is attributed to the simultaneously excited dual modes in a single resonator under lateral incidence. A large group index accompanied with a sharp EIT-like transparency window offers potential applications for slowing down light and sensing.

Keywords: metamaterial, electromagnetically induced transparency, slowing down light, sensing

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1. Introduction

In recent years, a lot of efforts have been devoted to metamaterials due to their unique properties and potentials for broad applications. The analogue of electromagnetically induced transparency (EIT) is only a part of the interesting work in metamaterials.[1–5] The EIT-like effect in a metamaterial is a phenomenon that closely mimics atomic systems. It can turn an originally opaque medium into a transparent medium in a certain frequency range for the incident electromagnetic waves. Intriguingly, the resonant transmission band is accompanied by a steep dispersion of the phase advance, thus the EIT-like window in metamaterial is very useful for many potential applications, such as slowing-down light,[6,7] filtering,[8,9] and sensing.[10,11]

Nowadays, researchers have discovered a lot of EIT-like phenomena in many metamaterials. The essence of the metamaterial analogue of the EIT effect is the destructive interference between two different excitation pathways. These EIT-like metamaterials usually have two types.[12–23] The first type is composed of a single resonator of an asymmetric structure, such as asymmetric split ring resonator (ASRR).[12] However, for a symmetric single resonator, usually only one resonant mode (e.g., a dipolar resonance) can be excited at a certain frequency. To obtain a two-mode interfered EIT-like effect in metamaterial, a second resonant mode with a different quality factor is necessary and generally it is introduced by breaking the symmetry of the single-resonator-based metamaterial. The second type is composed of multi-resonators of either symmetric or asymmetric structures, offering two different excitation pathways that couple in a way of destructive interference, thus leading to an EIT-like transparency window in the spectrum. In a usual case, the low-quality-factor resonance is called a bright mode which is directly excited from the far-field region, since it couples well to the free space. Its near-field map is usually characterized by an electric dipolar mode. On the contrary, the high-quality-factor resonance is usually called a dark mode, which can only be excited by the near field, since it does not couple strictly to the free space. The near-field map of a dark mode is characterized in most cases by an electric quadrupole mode or magnetic dipolar mode.[24–29] Recently, the EIT-like phenomenon has been demonstrated in a sample constructed by a single, but asymmetric, U-shaped resonator, or by a complex design of multi-resonators with two different U-shaped geometries.[21,23] However, no work has been reported on the EIT-like phenomenon that is obtained from a single symmetric U-shaped resonant metamaterial. In this paper, we propose a metallic metamaterial from which the EIT-like effect is excited by coupling two different excitation pathways in a single symmetric U-shaped metamaterial under the lateral incidence, in contrast to the normal incident cases in Refs. [21] and [23]. The destructive interference in our structure occurs between dual modes (i.e., the electric and magnetic dipole modes) that happen at the same frequency in the designed U resonator.

2. Numerical model

Copper is selected as the material of the single symmetric U-shaped resonator, and the thickness of the copper is 10 μm. The unit cell for the metamaterial array is comprised of a single symmetric U-shaped resonator with a size of 4.9 mm × 5.2 mm, and it is immersed in a host material with a permittivity of 2.1. More details about geometrical di-

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mensions of the U-shaped resonator are shown in Fig. 1(a). To investigate the electromagnetic response of this resonant structure, full-wave calculations were performed by a commercial package based on the finite-element method.[29,30]

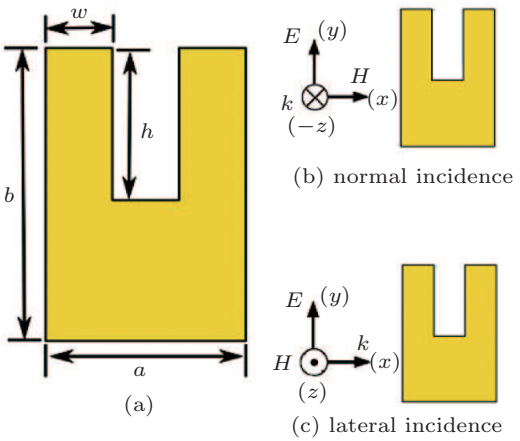


Fig. 1. (color online) (a) Schematic illustration of the metallic metamaterial and the detailed geometrical dimensions of the U-shaped resonator, where $a = 0.9$ mm, $b = 4.8$ mm, $h = 2.1$ mm, and $w = 0.4$ mm. (b) U-shaped resonator at normal incidence. (c) U-shaped resonator at lateral incidence.

3. Numerical results

We firstly calculate this U-shaped resonator at normal incidence (i.e., z axis is the propagation direction as shown in Fig. 1(b)) with the incident electric-field polarization along the b side of the structure (i.e., the normally incident field can be described by $E_{\mathrm{i}}^{\mathrm{nor}} = E_0\,\mathrm{e}^{\mathrm{i}(kz-wt)}$). Figure 2(a) shows the reflection and transmission spectra of the U-shaped structure. The square curve represents the transmission spectrum (S_{21}) and the triangle curve denotes the reflection spectrum (S_{11}). As can be found, the resonator supports a broad resonance around 22 GHz, this is called a bright mode and is directly excited by the incident microwave (this resonant frequency is mainly determined by the length b of the U-shaped structure and the size of the unit cell).

Now, we modify the propagation direction from the normal incidence to the lateral incidence (i.e., propagation along the x axis, as shown in Fig. 1(c)) and the electric field is polarized as well along the b side of the U-shaped resonator (i.e., the laterally incident field $E_{\mathrm{i}}^{\mathrm{lat}} = E_0\,\mathrm{e}^{\mathrm{i}(kx-wt)}$). As shown in Fig. 2(b), an interesting transparency window can be observed at about 22 GHz, which is in fact a typical EIT-like phenomenon in metamaterial. For the magnetic resonance, its frequency can be evaluated by the formula $f = 1/(2\pi\sqrt{LC})$. For a certain metal thickness, the inductance $L \propto h(a-2w)$ and the capacitance $C \propto 1/(a-2w)$. Therefore, the frequency of resonance is mainly determined by the size of the U-shaped structure. To gain a further understanding of the nature of this EIT-like transparency window, two illustrations in Figs. 3(a) and 3(b) show that the surface current distributions of the U-shaped structure at 22 GHz, corresponding to the normal and lateral incidence cases, respectively. It can be observed that the induced currents are in the same direction and predominately concentrate along the outer edge of the U-shaped resonator in Fig. 3(a), indicating that it is a pure bright mode (that is, electric dipolar mode) excited by the normally incident waves. In contrast, for the case of the laterally incident microwave shown in Fig. 3(b), it can be clearly observed that there is a circular current distribution around the inner edge of the U-shaped resonator, which manifests itself as the magnetic dipole resonance. Such a magnetic dipolar response is caused by the incident magnetic-field component parallel to the z axis. This magnetic dipolar resonance is a narrow resonance with a high quality factor (so-called dark mode), since it couples weakly to free space. At the same time, on the outer edges of both sides of the U shape, identically directed currents can be observed as a bright electric-dipole mode though it is relatively weak as compared with the dark magnetic-dipole response. Therefore, there are dual modes excited at 22 GHz. Namely, the dark mode which is sub-radiating to free space and the bright mode which radiates to free space. They couple to each other in such a fashion of destructive interference that an EIT-like transparency window is formed, as shown in Fig. 2(b). The overlapped mode current distribution indicates further evidence that the destructive interference can be induced in the single symmetric U-shaped resonator, contributing to the EIT-like phenomenon. However, for the normal incident case, this EIT-like phenomenon cannot be obtained in such a symmetric U-shaped structure [as presented in Fig. 2(a)], unless a symmetry-breaking configuration would be introduced.[23]

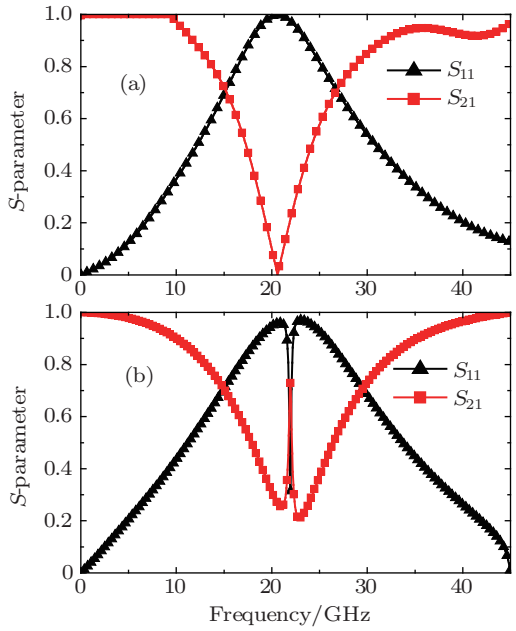


Fig. 2. (color online) Transmission and reflection spectra of the U-shaped resonator. (a) The normally incident case. (b) The laterally incident case.

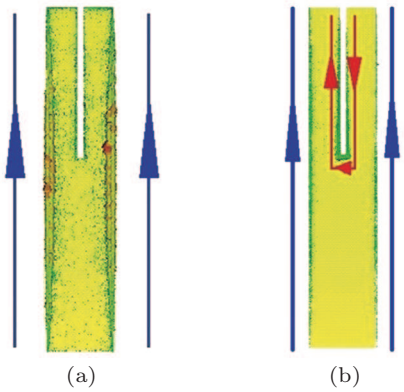


Fig. 3. (color online) Distributions of the induced surface current at resonance. (a) Induced bright electric-dipole mode at the normal incidence. (b) Dual modes of both the bright mode and the dark magnetic-dipole mode at the lateral incidence.

In order to further confirm that there are dual modes induced to provide two different excitation pathways for the EIT-like effect, we keep the other parameters unchanged except the value of h of the U-shaped resonator. It can be observed that the dual modes are now separated in the spectra shown in Fig. 4. From the transmission spectrum in Fig. 4(a) under the condition of $h = 1.6$ mm for the U-shaped resonator, there is a broad resonance at about 22 GHz and a narrow resonance at about 27 GHz. The broad resonance is a bright mode which is radiative and is excited by the polarized electric-field component of the incidence, while the narrow resonance is a dark mode which is non-radiative and is excited by the incident magnetic-field component polarized along the z axis. Figure 4(b) clearly shows, as can be expected, an EIT-like phenomenon at about 22 GHz since the frequency of the dark mode is about the same as that of the bright mode. It can also be found that the quality factor of the transparent window is very high for $h = 2.1$ mm in the U-shaped resonator. Figure 4(c) shows the transmission spectrum for $h = 2.6$ mm in the U-shaped resonator, and also exhibits a broad resonance and a narrow resonance separated like the result in Fig. 4(a), except that the narrow magnetic-dipole resonance is shifted toward the left side of the broad electric dipole resonance. If the value of h continues to increase, the broad resonance remains at 22 GHz and the narrow resonance continues to be red-shifted as indicated in Fig. 4(d). And the electromagnetic wave transmission can be evaluated by the formula:[31,32] $T \sim T_0(\omega + q)^2/(\omega^2 + 1)$. Here, q is the Fano factor that determines the asymmetric spectral line, ω is the frequency, and T_0 is the transmittance of continuum state. From these results shown in Figs. 4(a)–4(d), it is found that the frequency of the bright mode is unchanged throughout the variation of h, because it is directly dependent on the outer edge length of the U-shaped resonator and has nothing to do with the value h of the inner cut. But the frequency of the dark mode will be red-shifted with the value of h increasing, since the magnetic dipole is directly determined by the inner perimeter of the U-shaped resonator. As a result, the bright mode and the dark mode can occur at the same frequency by modulating the geometric parameter h, so that simultaneously excited dual modes can be realized by only a single resonator, without introducing a symmetry-breaking configuration. Consequently, the dual bright and dark modes will suffer a destructive interference and thus an EIT-like effect is observed.

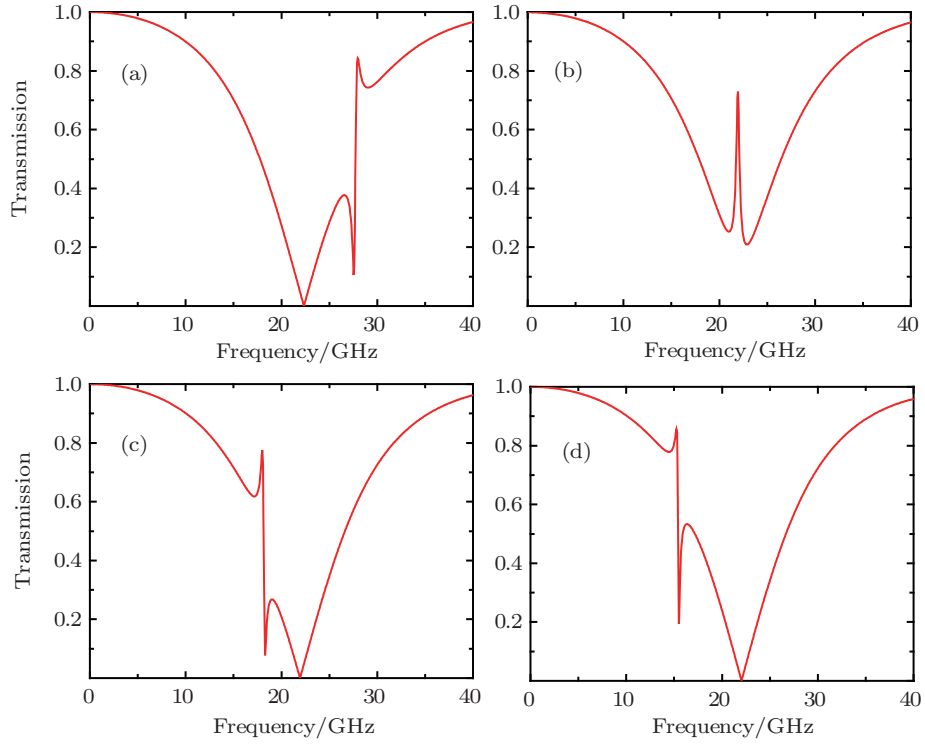


Fig. 4. (color online) Transmission spectra with different values of h: (a) $h = 1.6$ mm, (b) $h = 2.1$ mm, (c) $h = 2.6$ mm, and (d) $h = 3.1$ mm.

Figure 5 presents the frequency-dependent group index (n) and phase advance. The group index is calculated according to the following formula:[33,34]

$$n = c_0 \frac{\mathrm{d}k}{\mathrm{d}\omega} = \frac{c_0}{a} \frac{\mathrm{d}\phi}{\mathrm{d}\omega}. \quad (1)$$

Here, c_0 is the speed of light in vacuum, ω is the angular frequency, a is the width of the U-shaped resonator as the propagation distance of the electromagnetic wave, and ϕ is the phase advance. An enlarged group index of refraction is observed to be more than 100 around 22 GHz, corresponding to the EIT-like sharp transparency window. This is caused by the strong dispersion of the phase advance (the circlular curve in Fig. 5), similar to the EIT phenomenon of natural system. As is well known, a large group index of refraction means an increased traversing time through the entire structure, an effect that is the so-called slowing down of light.

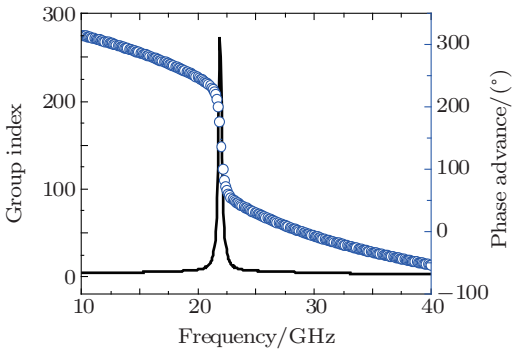


Fig. 5. (color online) Dependences of group index (solid curve) and phase advance (circle curve) on frequency of the incident wave.

4. Summary and conclusion

In this paper, we demonstrate an analogous phenomenon of EIT in a single-resonator-based symmetric metamaterial by numerical simulations. Under appropriate parameters of the U-shaped structure, there will be a coupling of the simultaneously excited dual modes of dark and bright resonances, which leads to an EIT-like resonant spectrum. The transparency window is extremely sharp and is accompanied by a large group index which can be exploited to design light-slowing devices and to enhance the sensibility to environmental change of index of refraction.

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