Physics Letters A ••• (••••) •••–•••

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Physics Letters A

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Tailoring polarization of electromagnetically induced transparency based on non-centrosymmetric metasurfaces

Hai-ming Li [a], Feng Xue [b]

[a] College of Telecommunications & Information Engineering, Nanjing University of Posts and Telecommunications, Nanjing, 210003, China
[b] Key Laboratory of Radar Imaging and Microwave Photonics, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, China

A R T I C L E I N F O

Article history:
Received 4 May 2017
Received in revised form 16 July 2017
Accepted 18 July 2017
Available online xxxx
Communicated by L. Ghivelder

Keywords:
Electromagnetically induced transparency
Slow light

A B S T R A C T

In this manuscript, tailoring polarization of analogy of electromagnetically induced transparency (EIT-like) based on non-centrosymmetric metasurfaces has been numerically and experimentally demonstrated. The EIT-like metamaterial is composed of a rectangle ring and two cut wires. The rectangle ring and the cut wire are chosen as the bright mode and the quasi-dark mode, respectively. Under the incident electromagnetic wave excitation, a polarization insensitive EIT-like transmission window can be observed at specific polarization angles. Within the transmission window, the phase steeply changes, which leads to the large group index. Tailoring polarization of EIT-like metamaterial with large group index at specific polarization angles may have potential application in slow light devices.

1. Introduction

Electromagnetically induced transparency (EIT) is an import coherent interference phenomenon in a three-level atomic system, and it causes a sharp narrowband transparency window within a broad absorption spectrum [1,2]. Within the transparency window, the phase steeply changes, which leads to large group index. All of above characteristics make EIT to have potential application in ultraslow light propagation [3], optical data storage [4], sensors [5–8] and optical switching [9]. However, the EIT in atomic system needs harsh experimental environment [10], which has significantly hampered the application. Recently, more attentions have been drawn to metamaterial analogy of EIT [11–19], which don't need harsh experimental environment and are easy to fabricate. Therefore, the EIT-like provide more effective ways to investigate the EIT behaviors. Most of previous EIT-like are based on "trapped mode" [20–24] and "bright-dark mode" [25–27]. However, in this manuscript, we use the destructive interference of the bright mode and the quasi-dark mode to generate EIT-like [6,28–30]. The bright mode and the quasi-dark mode can be both excited by incident electromagnetic wave. But, the bright mode have lower Q factor than that of the quasi-dark mode. Polarization insensitive EIT-like have potential application in slow devices, therefore, lots of polarization insensitive EIT-like [31–35] have been numerically and experimentally demonstrated. Those polarization insensitive EIT-like [31–35] are all based on centrosymmetric structure. In this manuscript, we propose an effective way to tailor polarization of EIT-like with non-centrosymmetric metasurfaces at specific polarization angle.

2. Results and discussion

Fig. 1(a) schematically depicts the cut wire's unit structure. The cut wire is copper and patterned on the FR-4 substrate. The geometrical parameters are as follow: $a = 16$ mm, $b = 16$ mm, $l_1 = 10$ mm, $w_1 = 0.5$ mm and $h = 1$ mm. Under the incident electromagnetic wave irradiation with electric field polarize along x axis, a electronic resonance can be excited, as shown in Fig. 1(b). The simulated transmission spectra is carried out by using the commercial finite difference time domain software package (CST Microwave Studio). The frequency of the electronic resonance is located at 9.35 GHz and the corresponding Q factor is 9. The Q factor can be calculated by the ratio of resonance frequency to the full width at half maximum.

Fig. 2 depicts the rectangle ring's unit structure and the corresponding transmission spectra, respectively. The rectangle ring is copper and patterned on the FR-4 substrate. The geometrical parameters are as follow: $a = 16$ mm, $b = 16$ mm, $l_2 = 10$ mm, $w_2 = 1.5$ mm and $h = 1$ mm. When planar electromagnetic wave is incident from the minus direction of z axis, a polarization insensitive electronic resonance at specific polarization angles of 0° can be observed in Fig. 2(b). The transmission dip is located at 8.85 GHz, and the corresponding Q factor is 3.

E-mail address: lhmm24@163.com (H.-m. Li).

http://dx.doi.org/10.1016/j.physleta.2017.07.025
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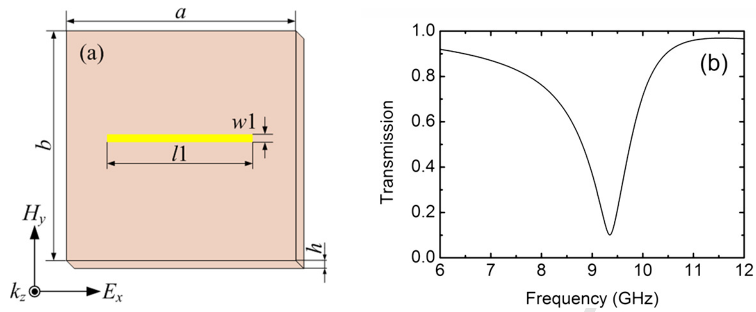

Fig. 1. (a) Schematic view of the cut wire's unit structure. (b) Simulated transmission spectrum of the cut wire.

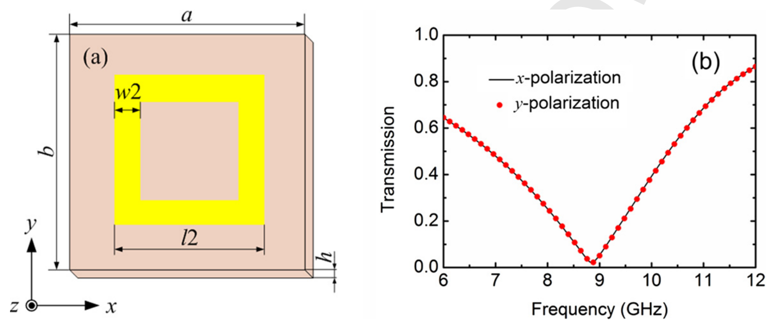

Fig. 2. (a) Schematic view of the rectangle ring's unit structure. (b) Simulated transmission spectrum of the rectangle ring at specific polarization angles of 0°.

The Q factor of the cut wire is larger than that of the rectangle ring. Thence, the rectangle ring and the cut wire are chosen as the bright mode and the quasi-dark mode, respectively. The difference between the bright mode and the quasi-dark mode is $\Delta f = 0.5$ GHz, which is much smaller than the frequency of either the bright mode or the quasi-dark mode. When the two cut wires and a rectangle ringlet are put together, a polarization insensitive EIT-like at specific polarization angles can be generated. Fig. 3(a) schematically depicts the EIT-like unit structure. The EIT-like metamaterial is composed of a rectangle ring and two cut wires. The rectangle ring and the cut wires are patterned on the FR-4 substrate. The coupling distance between the rectangle ring and two cut wires are $d_1 = 1.2$ mm and $d_2 = 1.2$ mm. The other geometrical parameters are shown in Fig. 1(a) and 2(a). Fig. 3(b) is the photography of the fabricated EIT-like metamaterial. Under incident electromagnetic wave irradiation, the metamaterial exhibits the polarization insensitive EIT-like transmission window at specific polarization angles of 0°, as illustrated in Fig. 3(c). A narrow transmission peak ($f_2 = 8.45$ GHz) located between two transmission dips ($f_1 = 8.05$ GHz and $f_3 = 9.92$ GHz) can be clearly observed. The experimental measurements are completed in the microwave anechoic chamber with a vector network analyzer (N5230C) and a pair of linearly polarized broadband horn antennas. The experimental results show a good agreement with the simulated magnitudes, as demonstrated in Fig. 3(d). We can see the transmission phase change steeply within the transmission window from Fig. 3(e), which leads to large group index. The group index (n_g) can be obtained according to the following formula:

$$n_g = -\frac{c_0}{H} \cdot \frac{\mathrm{d}\varphi(\omega)}{\mathrm{d}\omega}$$

where the c_0 is the speed of light in vacuum, the $\varphi(\omega)$ is phase, the ω is angular frequency and the H is the thickness of the metal-dielectric metamaterial system. From Fig. 3(d), we can see the group index steeply changes and exhibits the strong dispersion within the transmission window. We can also see that the group index can reach to 185 at the transmission peak. The polarization insensitive transmission spectrum with such a large group index may have potential application in slow light devices.

In order to obtain the influence of thickness H on the slow light effect, Fig. 4 shows the simulated transmission spectrum and the group index of EIT-like metamaterial with different thickness H. From Fig. 4(a), we can find that transmission spectrum shift to low frequency range with increasing H. However, the transmission peaks of EIT-like metamaterial are almost the same with increasing H. From Fig. 4(b), we can find that the group indexes shift to low frequency range with increasing H. Meanwhile, the value of group indexes gradually reduced with increasing H, which means that the slow light effect of EIT-like metamaterial gradually degenerate with increasing H.

Fig. 5 shows that the EIT-like metamaterial can exhibit polarization insensitive transmission spectrum at specific polarization angles. From Fig. 5, we can find that x-polarization transmission spectrum of the EIT-like metamaterial are almost unchanged at polarization angles of 0°, 90°, 180° and 270°. The x-polarization incident electric field is 90° out-of phase with the y-polarization incident electric field. Therefore, y-polarization transmission spectrum are same with x-polarization transmission spectrum. The polarization insensitive transmission spectrum are ascribe to the unique unit structure of EIT-like metamaterial. At specific polarization angles of 0°, 90°, 180° and 270°, the rectangle ring is same and the cut wires are respectively located at directions parallel to x and y axis, which makes the cut wires have identical response to either x-polarization or y-polarization incident electromagnetic wave. Therefore, the EIT-like metamaterial exhibits the polarization insensitive transmission spectrum at specific polarization angles of 0°, 90°, 180° and 270°.

In order to visualize the underlying physics of the EIT-like metamaterial, the surface current distributions of the transmission peak and dips under y-polarization are depicted in Fig. 6. The y-polarization means the electronic field component of incident electromagnetically wave is along the y axis. At the transmission peak ($f_2 = 8.45$ GHz), the surface currents along the rectangle ring are suppressed and almost all of surface currents are concentrated on the surface of the left cut wire, which are caused

Please cite this article in press as: H.-m. Li, F. Xue, Tailoring polarization of electromagnetically induced transparency based on non-centrosymmetric metasurfaces, Phys. Lett. A (2017), http://dx.doi.org/10.1016/j.physleta.2017.07.025