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Voltage Control of Electromagnetically-Induced-Transparency-Like Effect in Metamaterials Based on Microstrip System

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Abstract—The tuning of electromagnetically-induced-transparency-like (EIT-like) phenomenon in metamaterials based on microstrip system is investigated. The tunability of EIT-like effect mainly arises from the controllable elements of varactor diodes loading on the "dark" resonators of EIT-like metamaterials. The results show that the frequency range of transparency window of our EIT-like metamaterials can be continuously and reversibly adjusted along with the varying external voltages applied on the varactor diodes. Moreover, the transmittance maximum hardly changes with the shift of transparency window. Such tunable EIT-like metamaterials may be applied in tunable slow-wave filters and switch devices.

1. INTRODUCTION

Electromagnetically-induced-transparency (EIT) is a typical quantum interference phenomenon that occurs in an atomic system leading to an extremely narrowband transparency window within a wide absorption line [1, 2]. In the EIT system, a very steep dispersion is created along with the transparency window, which can be used for slow light or the storage of light [3, 4]. However, cumbersome experimental conditions are often involved in achieving EIT phenomenon, such as large power lasers, cryogenic temperatures and high magnetic field, which greatly limit the applications of quantum EIT. Recent studies have shown that EIT effect can be mimicked by non-quatum approaches, such as optical waveguide [5–8] and photonic crystals [9, 10]. In addition, metamaterial, as an artificial subwavelength structure, exhibits lots of unique properties and has many extraordinary applications [11–13]. In recent years, metamaterial analogy of EIT phenomenon has also attracted considerable attention and various structures have been proposed [14–29]. In 2008, Zhang et al. demonstrated that a metamaterial molecule composed of a pair of "bright" and "dark" resonators can serve as a three-level "atom" with EIT-like properties, which was experimentally investigated by Giessen et al., soon [14–16]. Metallic fish-scals, U-shaped structure, ring resonators and some other structures were also employed to illustrate the EIT-like slow light effect in metamaterials [17–29]. Especially, in Ref. [22] a kind of EIT-like metamaterial based on microstrip line was proposed.

The tunability of EIT-like effect in metamaterials is another key issue which has also aroused interests of many researchers. Generally, the properties of EIT-like effect can be controlled by the design of metamaterial unit cell such as changing the separation of "bright" and "dark" resonators, varying the displacement of one resonator, altering the rotation angle of the resonator, and so on [14–16, 24, 25]. As we know, the changes of separation, displacement and rotation angle are extremely difficult once the EIT-like metamaterials are fabricated. In Refs. [26–29], the authors realized active tuning of EIT-like effect through temperature control or changing the incident angle. However, we

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find that the frequency range of transparency window of EIT-like metamaterials can not be tuned when varying the incident angle. Although the transparency window can be shifed, the transmittace maximum of transparency window possesses a huge difference for superconductor-based EIT-like metamaterials controlled by temperature.

In this letter, a tunable EIT-like metamaterial based on microstrip system is designed based on the structure presented in Ref. [22] and the voltage control of EIT-like effect is investigated. The results show that the frequency range of transparency window can be continuously and reversibly adjusted along with the varying external voltages applied on the varactor diodes loading on the "dark" resonators of EIT-like metamaterials. Moreover, the transmittance maximum of our structure hardly changes with the shift of transparency window. Such tunable EIT-like metamaterials may be useful for applications in tunable slow-wave filters and switch devices.

2. SIMULATION

First, we investigate the feasibility of realizing tunable EIT-like metamaterial based on the atomic-like three-level system proposed in Ref. [22] through full-wave simulation. As we know, the resonant frequency of the double split ring resonators (DSRRs) will change along with the variation of capacitance values, when the capacitor is introduced between two split ring resonators (SRRs), as shown in Figure 1(a) [30]. Then, the transmission properties of the whole structure shown in Figure 1(a) should be affected by the change of the capacitance values. The transmission properties (denoted by the magnitude of the transmission coefficient, $|S_{21}|$) of the structure shown in Figure 1(a) under various capacitance values are simulated by CST microwave studio based on finite integration technique (FIT) under the electrical boundary condition and depicted in Figure 1(b). In order to be realized in experiment, for our simulation, the microstrip line is designed with strip width 2.96 mm to match the characteristic impedances 50 Ω. The relative permittivity and thickness of the substrate is $\varepsilon_r = 4.75$ and $h = 1.6$ mm respectively. The length and width of the comb line are $l = 21.5$ mm and $u = 0.4$ mm respectively. The edge length of outer SRR is 7.5 mm. The wire width and gap size are $w = 0.5$ mm and $g = 0.4$ mm for the outer and inner SRRs. The space of the inner and outer SRRs in the right side is $n = 1.8$ mm and for other three sides, the distance is all $m = 0.3$ mm. The separation between DSRRs and comb line is $p = 0.4$ mm. From Figure 1(b) it can be seen that the transparency window shifts gradually to higher frequencies with the decrease of capacitance value. Therefore, the tunable EIT-like metamaterial can be realized if the capacitor is replaced by the varactor diodes.

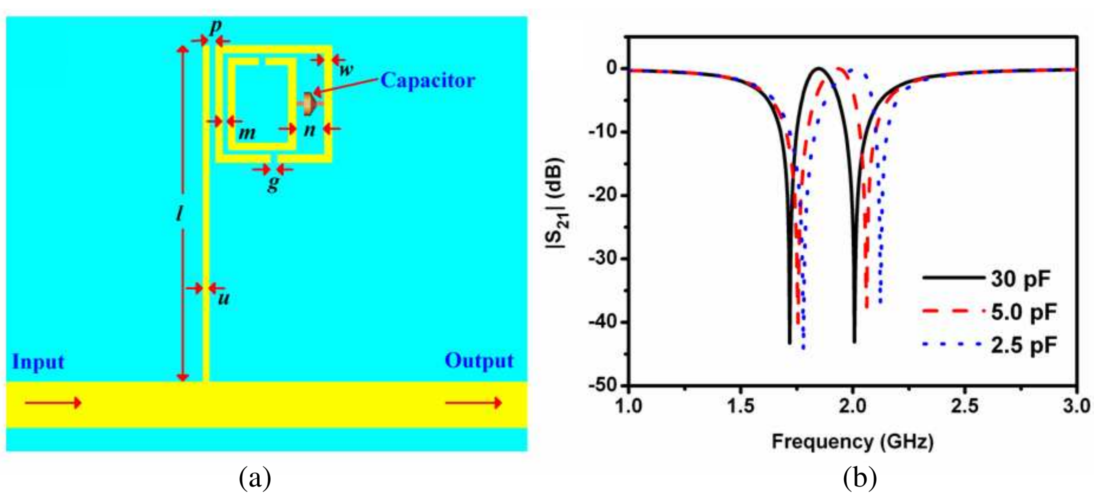

Figure 1. (a) The schematic of the EIT-like metamaterial employed in simulation. (b) The simulated transmission spectra of the structure shown in (a) under various capacitance values.

3. EXPERIMENT

According to the above numerical analysis, we design the tunable EIT-like metamaterial based on microstrip transmission line by introducing varactor diodes into the "dark" resonators, as shown in Figure 2. The structure includes two identical unit cells to make the transparency window have a larger variation range. Therein, one unit cell consists of an open-ended comb line connected to the center strip of microstrip transmission line, which acts as the "bright" resonator and a varactor-loaded DSRRs playing the role of "dark" resonator. The geometric parameters of our sample are labeled in Figure 2 and they are identical with the simulation. The length and width of the comb line are also $l = 21.5$ mm and $u = 0.4$ mm respectively. The edge length of outer SRR is $a = 7.5$ mm. For the outer and inner SRRs, the wire width and gap size are also $w = 0.5$ mm and $g = 0.4$ mm. The space of the inner and outer SRRs in the right side is also $n = 1.8$ mm and for other three sides, the distance is all $m = 0.3$ mm. The separation between DSRRs and comb line is also $p = 0.4$ mm. Direct current (DC) power is applied on the varactor diodes through restricting circuit resistors and series radio frequency chokes (RFC) used to separate the alternating current (AC) signal network from the DC power supply. The wire denoted by V_+ is connected to the positive electrode of DC power supply, as well as the cathode of DC power supply is connected to the ground plane of microstrip line. In addition, the parameters of the substrate and the strip width of the microstrip line is also the same as the simulation.

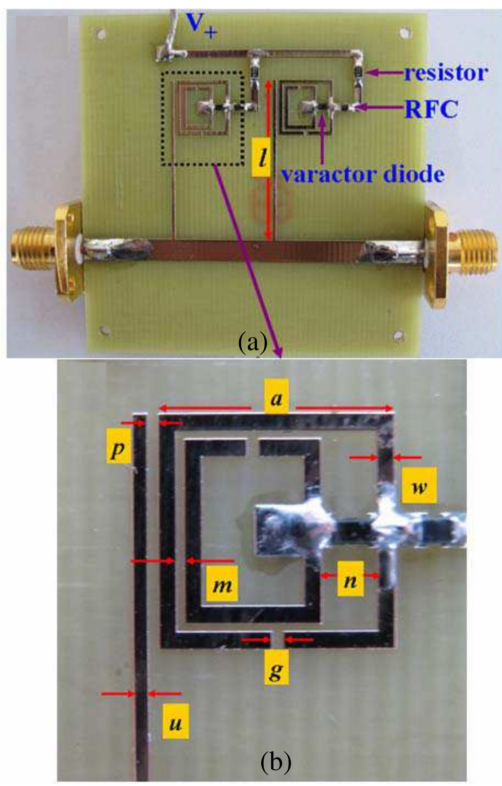

Figure 2. The photograph of the tunable EIT-like metamaterial based on microstrip line.

Next, we investigate the tunable properties of the structure shown in Figure 2. The transmission curves of the structure under various bias voltages are measured (by Agilent N5244A vector network analyzer) and plotted in Figure 3. In Figure 3, the typical EIT spectral response, in which a protruding transparency window locates within two frequency stop bands, is observed and the transparency window shifts gradually to higher frequencies with the increase of bias voltages. The tuning range is about 10% when the voltage changes from 0 to 16 V. As the change of capacitance value of varactor diode results in the variation of the transparency window, the tuning range of the EIT-like metamaterials is strongly dependent on the variation range of the capacitance values of the varactor diodes. Moreover, the measured results also demonstrate that the voltage dependence of the transparency window is reversible. In particular, different from the pre-existing tunable EIT-like metamaterials, for instance, superconductor-based EIT-like metamaterials, our structure has the characteristic of almost changless transmittance maximum with the shift of transparency window. With these features, such tunable EIT-like metamaterials may be useful for applications in tunable slow-wave filters and other related devices.

In addition, when comparing the transmission spectra of the tunable EIT-like metamaterial at the voltages of 0 and 21 V, we find that for the selected frequency $f_0 = 2.084$ GHz, the transmittance maximum of transparency window is obtained at the voltage of 21 V, while it is the resonance dip at 0 V, as shown in Figure 4. That is to say, for the fixed frequency $f_0 = 2.084$ GHz, our structure is transparent to the electromagnetic wave under the voltage of 21 V, whereas it is opaque at 0 V. Therefore, such tunable EIT-like metamaterials also promise potential applications in design of switch devices.

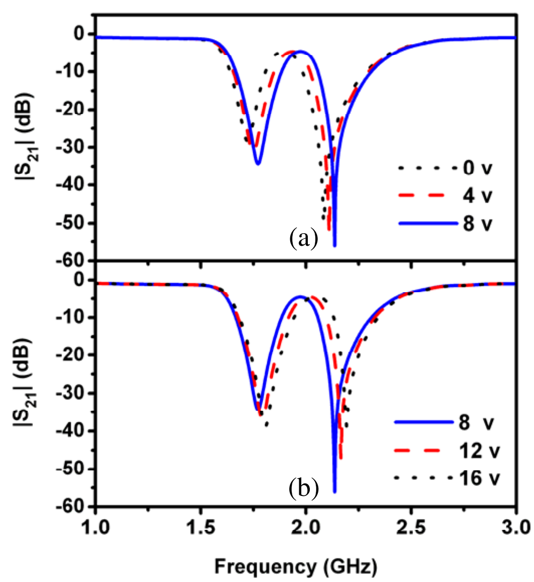

Figure 3. The measured transmission spectra for the EIT-like metamaterial based on microstrip line at various bias voltages.

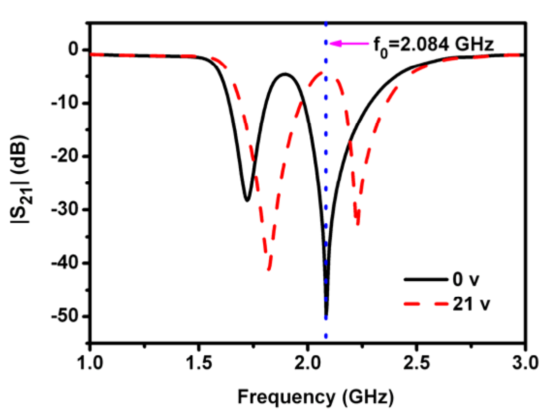

Figure 4. Comparison of transmission spectra of the tunable EIT-like metamaterial under the voltages of 0 and 21 V.

4. CONCLUSION

In conclusion, we investigate the tuning of EIT-like phenomenon in metamaterials based on microstrip system. The results show that the frequency range of transparency window of our EIT-like metamaterials can be continuously and reversibly adjusted along with the varying external voltage applied on the varactor diodes. Meanwhile, the structure also has the characteristic of almost changeless transmittance maximum with the shift of transparency window. The proposed tunable EIT-like metamaterials may have potential applications in tunable slow-wave filters, switch devices, etc.

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