Active Modulation of an All-Dielectric Metasurface Analogue of Electromagnetically Induced Transparency in Terahertz

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ABSTRACT: In this work, an analogue of electromagnetically induced transparency (EIT) is excited by a periodic unit consisting of a silicon rectangular bar resonator and a silicon ring resonator in terahertz (THz). The analogue of the EIT effect can be well excited by coupling of the “bright mode” and the “dark mode” supported by the bar and the ring, respectively. Using the semimetallic properties of graphene, active control of the EIT-like effect can be realized by integrating a monolayer graphene into THz metamaterials. By adjusting the Fermi energy of graphene, the resonating electron distribution changes in the dielectric structures, resulting in the varying of the EIT-like effect. The transmission can be modulated from 0.9 to 0.3 with the Fermi energy of graphene placed under the ring resonator mold varying from 0 to 0.6 eV, while a modulation range of 0.9−0.3 corresponds to Fermi energy from 0 to 0.3 eV when graphene is placed under the rectangular bar resonator. Our results may provide potential applications in slow light devices and an ultrafast optical signal.

1. INTRODUCTION

The electromagnetically induced transparency (EIT) phenomenon is originally proposed by Harris in atomic physics, forming a narrow transparent window within a broad absorption band of light, which is the result of destructive quantum interference in a three-energy-atom system. The feature of strong dispersion in the narrow transparent window makes it advantageous for applications in slow light, nonlinear enhancement, sensing devices, group delay, and so on. Recently, this concept was extended to an analogue of EIT in plasmonic metamaterials because of their simple structure and ease of operation. The classical analogue of EIT originates from the coupling of the bright mode and dark mode. The bright mode is a resonant mode excited directly by the incident wave. Meanwhile, the dark mode cannot be excited directly by the incident wave but it can be excited by the bright mode, thus resulting in an EIT-like effect. Initially, metal is used to achieve the EIT-like effect. Fedotov’s research group designed a planar periodic array of asymmetric splitting rings composed of two arcs in different lengths, which provided an extremely narrow transmission. Then, multifarious structures have been proposed gradually, for example, split-ring resonators (SRRs), bar resonator with SRRs, and so on, which have shown great prospects in optical filters and ultrasensitive biosensors. However, the metal coupling excitation of the EIT-like effect is associated with high radiation losses, which limits achieving high transmission, a high Q-factor, or a large group index. So, the analogue of EIT by dielectric metamaterials has attracted enormous interest. Yang’s research group experimentally demonstrated an analogue of the EIT effect using a silicon-based metasurface, which avoids high radiation losses and a Q-factor of 483 is observed. Now, more and more all-dielectric structures can realize the EIT-like effect with a perfect narrow transparent window.

For practical applications, active tuning of metamaterials has attracted great interest in terahertz due to its ultrafast modulation speed and switching capabilities. It is troublesome to passively control the EIT-like effect via changing the geometric parameters of the resonator structure. Gu’s research group initially demonstrated a method of active controlling the EIT-like effect by integrating photoconductive silicon into a metamaterial unit cell in THz. Graphene is a monolayer carbon material, which is an interesting experimental material due to its unique electronic and optical properties. The active tuning of the terahertz resonance can be realized simply and economically as graphene is a tunable material. The transmission in the EIT-like effect can be modulated from 0.9 to 0.3 with the Fermi energy of graphene placed under the ring resonator mold varying from 0 to 0.6 eV, while a modulation range of 0.9−0.3 corresponds to Fermi energy from 0 to 0.3 eV when graphene is placed under the rectangular bar resonator. Our results may provide potential applications in slow light devices and an ultrafast optical signal.

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optical material, which can be characterized by its photoconductivity.\textsuperscript{[10–32]} Xiao’s research group proposed a graphene metamaterial terahertz modulator, in which the structure is composed of a cut wire (CW) and SRRs, realizing an active modulation in the transmission peak value of the EIT-like effect by operating the Fermi energy of graphene.\textsuperscript{33} It is possible to actively tune all-dielectric EIT-like effects through the tuning properties of graphene.\textsuperscript{34–36} However, active tuning of all-dielectric THz metamaterials via graphene has been rarely reported.

In this article, we propose, for the first time to the best of our knowledge, the use of graphene for active regulation in all-dielectric EIT-like metamaterials. The EIT-like effect is realized through the structure consisting of a silicon ring resonator and a silicon rectangular bar resonator. Utilizing the semimetallic properties of graphene, the quantum interference between the two resonant modes is influenced. First, we place the graphene beneath the silicon ring resonator. The transmission peak value gradually decays from 0.9 to 0.3 by changing the Fermi energy of graphene from 0 to 0.6 eV. Then, the graphene is placed under the rectangular bar resonator, and the modulation range is 0.9–0.3 when the Fermi energy of graphene varies from 0 to 0.3 eV. The principle of the regulation is analyzed through the image of the electromagnetic field. In addition, the real and the imaginary parts of the graphene conductivity depend on the frequency at the selected values of the Fermi energy, which further elucidate the physical underpinnings of the EIT-like metamaterials.\textsuperscript{37} It may attract interest in developing electronic tunable EIT-like metamaterials and have a good promoting effect on slow light, light switch, and so on.

2. RESULTS AND DISCUSSION

As shown in Figure 1a, the structure consists of a silicon ring resonator and a silicon rectangular bar resonator. The incident E-field is along the X-axis. The sample array occupies an area of $150 \times 150 \mu m^2$ and the spacing between each cell is 16 $\mu m$. The parameters of each cell are $r_1 = 45 \mu m$, $r_2 = 22 \mu m$, $d_1 = 30 \mu m$, $l_1 = 144 \mu m$, and $g_1 = 14 \mu m$, respectively. (b) Transmission spectra of the structures with the rectangular bar and ring resonator (black curve); the structures with ring resonator only (red curve) and with rectangular bar resonator only (blue curve).

![Figure 1](https://example.com/figure1.png)

E-field is along the X-axis. The sample array occupies an area of $150 \times 150 \mu m^2$, and the spacing between each cell is 16 $\mu m$. The parameters of each cell are $r_1 = 45 \mu m$, $r_2 = 22 \mu m$, $d_1 = 30 \mu m$, $l_1 = 144 \mu m$, and $g_1 = 14 \mu m$, respectively. In addition, the thickness of Si is $3.7$ $\mu m$, the substrate material is a medium with index $n = 1.48$. The numerical simulations are conducted using the finite-difference time-domain method (FDTD). Here, the boundary conditions are periodic boundary conditions in the X and Y directions and perfect matching layers in the Z direction. The discretization of space adopts 0.1 times of the metallic structure’s size, and the calculation stops automatically when the running time is nearly 1200 ps.

Simulated transmission spectra are shown in Figure 1b. For the structure with both ring and rectangular bar resonator, a narrow transparent window can be expressly observed at 1.11 THz. High transmission occurs in the effective range because the polarization of the incident plane wave has retained structural symmetry. The above principle can be well verified, but a transmission peak may occur due to the uneven environment caused by the segmentation of the ring (red curve). Only when the rectangular bar exists, a distinct projection peak appears at 1.12 THz (blue curve), which is the basic and direct response of metamaterials by the incident plane wave. As an electric dipole antenna, the rectangular bar resonator can be strongly coupled to the free space excitation caused by the electromagnetic energy incident along the X-axis, known as the “bright” mode, while the ring supports a magnetic dipole mode, in which the electromagnetic energy rotates along the axis of the ring in the azimuth direction, known as the “dark” mode. Since the magnetic arm of the incident wave is perpendicular to the dipole axis, the light cannot directly excite the magnetic dipole mode in the ring. Then, the bright mode couples with the dark mode, forming an analogue of the EIT effect.

Next, the graphene is placed under the ring resonator for adjustment to explore the active tuning of the all-dielectric EIT-like metamaterials. The length and width of graphene are $d_1 = 5 \mu m$ and $l_1 = 150 \mu m$, as shown in Figure 2a. With increasing graphene Fermi energy, the resonance intensity of EIT-like metamaterials at the specific resonance frequency is regulated without affecting adjacent spectra, as shown in Figure 2b. The transmission peak value gradually decays from 0.9 to 0.3 when the Fermi energy of graphene varies from 0 to 0.6 eV. Furthermore, the spectral contrast ratio is obviously seen. It can be found that when the transmission of EIT-like metamaterials reduces, the frequency shift occurs because of approaching the direct oscillation mode of the bright mode. Data simulation and analysis show that this modulation is due to the change of the dark mode damping rate because of increasing graphene conductivity. Thus, it causes an increase in spectral absorption, as shown in Figure 2c.

When the Fermi energy is 0.6 eV, the absorption can reach up to 0.5. As the electromagnetic properties of graphene change due to its Fermi energy, it has a significant impact on the surrounding electromagnetic energy, as shown in Figure 2d–g, which has a strong effect on the metamaterial resonance. In the absence of graphene, the electromagnetic energy was mainly concentrated in the ring resonator, suggesting that the dark mode was excited by the bright mode, which could well explain the emergence of an EIT-like phenomenon. With increasing Fermi energy of graphene, the intensity of the corresponding electromagnetic energy image weakens. Thus, the window formant and the Q-factor obviously decrease. Finally, the coupling strength between the electromagnetic fields reduces and the EIT-like effect weakens, consistent with the transmission spectra shown in Figure 2b. This illustrates that the EIT-like effect can be regulated by introducing graphene.

Similarly, we investigate the influence of graphene under the bar resonator in Figure 3a. In terms of parameters, graphene has $d_1 = 5 \mu m$ and $l_1 = 150 \mu m$. As shown in Figure 3b, the transmission peak value obviously decreases when the Fermi energy of graphene varies from 0 to 0.3 eV. The incident light
that resonates with the bar resonator is affected by the increase of the Fermi energy. When the Fermi energy is 0.2 eV, the transmission peak has an obvious decline compared to the device without graphene. Then, when \( E_F \) is to 0.3 eV, the transmission peak almost disappears. The absorption of the structure increases with increasing Fermi level of graphene, as shown in Figure 3c. Moreover, the saturation absorption of graphene leads to the adjustment amplitude of the EIT phenomenon. The electromagnetic energy of the corresponding Fermi energy of graphene is plotted to further elucidate the physical underpinnings of the active modulation of EIT-like metamaterials, as shown in Figure 3d-g. When the Fermi energy of graphene is 0 eV, the EIT-like effect in the ring resonator is excited by coupling with the bar resonator in a round-about way, and the electromagnetic energy is mainly distributed in the ring resonator, as shown in Figure 3d. With increasing Fermi energy, a change of the bright mode damping rate causes electromagnetic energy attenuation. As shown in Figure 3g, the electromagnetic energy decays to near zero, which shows that the destructive interference between the ring resonator and bar resonator resonance mode disappears. Therefore, we can adjust the Fermi energy of graphene according to practical requirements to achieve active regulation of EIT-like metamaterials.

To better explain the tuning principle of graphene, the real part and the imaginary part of the graphene conductivity at the frequency of 0.9–1.2 THz were calculated according to the equation, as shown in Figure 4a,b. It can be seen from the figure that the real part of graphene increases with increasing chemical potential from 0 to 0.3 eV, as well as the imaginary part. The doping charge density increases the Fermi energy to \( E_F = \frac{\mu}{e^2/n_d} \), so the higher charge density indicates the higher \( E_F \), resulting in higher loss and absorption. The electromagnetic waves induced by the dielectric metasurface and the absorption of the graphene layer are strongly coupled, so the reduction of the EIT effect may be related to increasing graphene absorption. With increasing graphene chemical formula, the electromagnetic energy attenuates significantly and the peak value decreases significantly, which can be attributed to the increase of the energy loss and absorption of the incident wave. It is clear that the origin of the EIT effect modulation is essentially the optically adjustable conductivity of the graphene.

3. CONCLUSIONS

In summary, we achieved active tuning of EIT analogue effects by integrating monolayer graphene into THz all-dielectric metamaterials. An obvious narrow band window can appear near the 1.1 THz frequency, which is excited by a silicon ring resonator and a silicon rectangular bar resonator in THz. Graphene with 0–0.6 eV was placed under the ring resonator mold with a transmission range of 0.9–0.3, and the EIT effect can be well tuned without affecting the adjacent spectrum. However, the modulation range is 0.9–0.3 for Fermi energy from 0 to 0.3 eV, when graphene is placed under the
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Notes
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■ ABBREVIATIONS
EIT, electromagnetically induced transparency; THz, terahertz; SRRs, split-ring resonators; CW, cut wire

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